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CONTENTS

Ventifacts and Eolian Sand at Charette, P.Q.

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ABSTRACT

The keels on 250 ventifacts, mostly einkanters, from stratified drift near Charette, P.Q., have a preferred azimuth of about 165°. The poles of the facets are concentrated at about 75° azimuth and plunge at about 55°. The effective wind as determined from the threshold velocity for the Charette sand and meteorological data from Montreal and Quebec is northeast, though prevailing winds are from the west. The attitude of wind-cut facets apparently indicates the direction of the strongest effective winds. Morphology of sand dunes and grain-size distributions suggest a wider range of effective wind directions ranging from northwest to northeast.

VENTIFACTS are stones that have been shaped by the impact of sand driven by the wind. They usually have flat or concave facets that join along a sharp ridge or keel, and the number of keels is used to describe the stones as einkanter, dreikanter, etc. The number of facets cut depends on the time available and the amount of sand movement, and has been used as an indication of the age of the deposits containing them by Mather, Goldthwait, and Thiesmeyer (11). Large ventifacts of boulder size or comprising part of a bedrock surface have been used as indicators of former humidity conditions (4) or to infer the directions of former effective winds (2; 7; 12). Smith (13) stated emphatically that small ventifacts are not valid indicators of wind direction, but the writers were unable to find any published statistical data to support or deny his contention. Qualitative work by Cailleux (5, pp. 51–6) showed a preferred orientation of facets on ventifacts ranging from about 8 to 30 centimetres in size in Iceland. Denny (6) found a random orientation of some ventifacts in Connecticut, and attributed it to their being disturbed after being shaped by the wind.

The senior author of this paper casually observed in the field that the keels of the ventifacts at Charette had the same general orientation and, following the view of Walther (15), he tentatively concluded that they were formed by wind from the north-northwest which was split by the stones resting on the sand so that sand flowed around both sides of the stone and carved facets separated by a sharp crest. Walther used this theory to explain the formation of dreikanter (more or less tetrahedral ventifacts) without undermining and overturning. His view is perpetuated, with qualifications, in some modern textbooks of geology (e.g., 10, pp. 271–2).

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The ventifacts at Charette were collected by the senior author with a view to examining the orientation of facets in the light of present-day or former wind directions. His thanks are due to Dr. André Deland of the Quebec Department of Mines for calling his attention to this occurrence.

THE CHARETTE VENTIFACT LOCALITY

Charette (see Fig. 1) is located on a ridge of glacial deposits known as the St. Narcisse moraine (9) which here comprises stratified sand and gravel. The ventifact locality (Fig. 2) is about one and one-half miles east of the village. The ventifacts were in an area of wind-blown sand on the crest and on the north slope of the ridge at an altitude of about 420 to 460 feet.
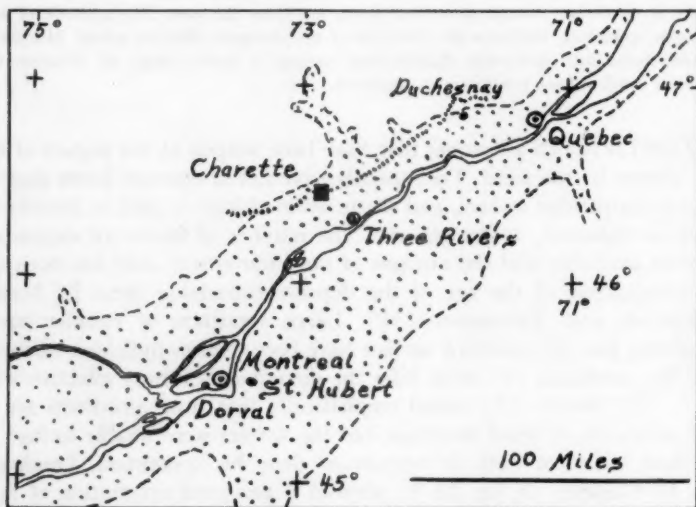
FIGURE 1. St. Lawrence Lowlands showing the location of Charette and the meteorological stations. Area of the Champlain Sea is stippled. The hachured line passing through Charette represents the St. Narcisse moraine.

Apart from the woods to the south and east of the ventifact site the only obstruction to winds is the hill about half a mile to the northeast where a segment of the moraine rises about 100 feet above the site. There are other hills as much as 200 feet higher about the locality but they are more than two miles distant, and are sufficiently scattered as to have minor or negligible effects on wind directions at Charette.

The ventifacts were collected in 1953–4, but their site was destroyed by the development of a gravel pit before the junior author visited it to collect sand specimens. A low dune 200 to 300 feet in length now extends south-
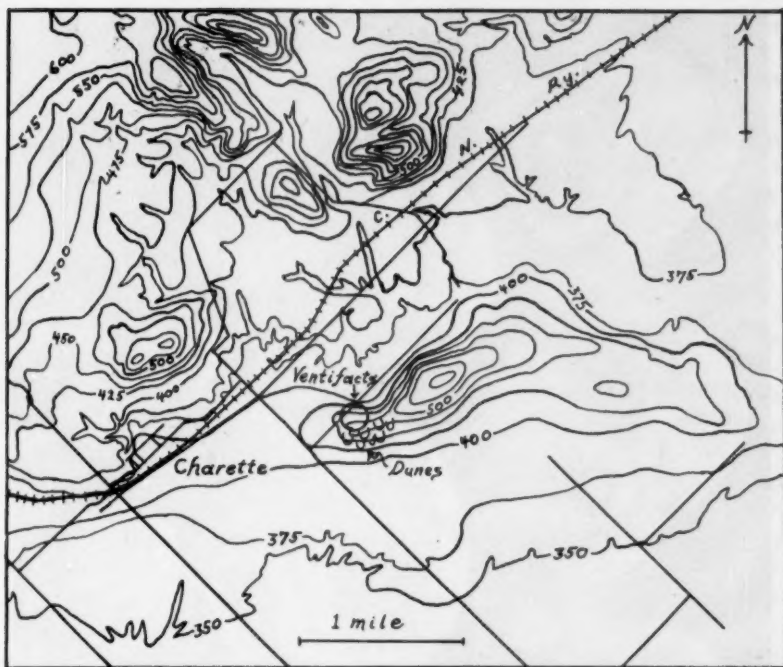
FIGURE 2. Topography in the vicinity of Charette showing hills that may influence wind movements. Contour interval is 25 feet. After National topographic map sheet 31 1/7, west half (Trois-Rivières).

ward from the gravel pit, and is assumed to have formed contemporaneously with the ventifacts. Older stabilized dunes are also present; all expanded south and east from the same source area.

At the times of the visits of both authors the sand ripples trended west, indicating that the last sand-moving winds were from the north quadrant.

THE VENTIFACTS

About 250 ventifacts were collected from the more or less horizontal upper surface of the ridge and about 60 more were collected just over the edge on the northern slope. All were marked *in situ* with a horizontal line and a north arrow. The length of the intermediate axes of the ventifacts ranges from 2 to 12 cm., 48 per cent being between 6 and 8 cm. Roughly 20 per cent are large pebbles. All stones were appreciably rounded by the action of water before they were sand-blasted, though most had several surfaces controlled by joints.

The lithology of the adjacent part of the Canadian Shield dominates;
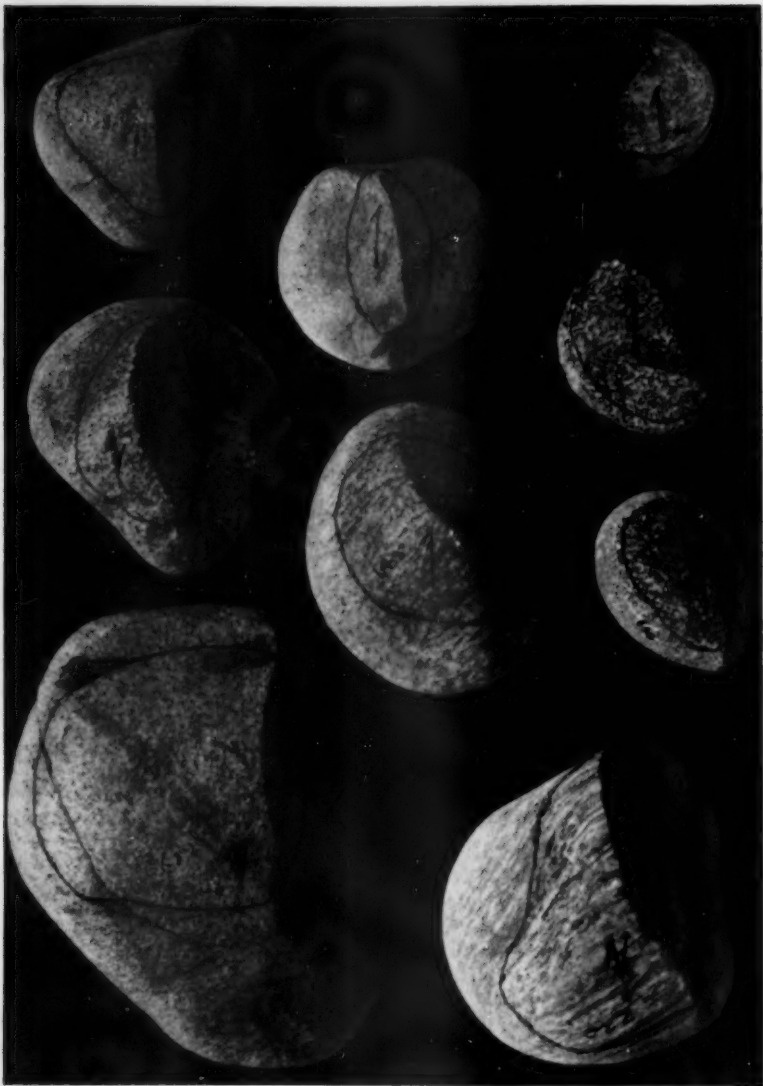
FIGURE 3. Representative ventifacts from the Charette locality. The largest (no. 172) is 11 to 12 cm. in width, the smallest shown (nos. 115 and 116) are 4 to 5 cm. wide. The closed lines are the traces of horizontal planes and the arrows point north; single barbs represent magnetic north, and double barbs are true north. The stones are oriented approximately as found *in situ*. Note that the deeply cut concave facets are mainly on the east sides. The faint crosses on several of the stones are merely guides for assistants who measured facet orientations.

granites and granite-gneisses comprise the bulk of the ventifacts and various metamorphic rocks are common.

Of the ventifacts found on the crest of the ridge about 34 per cent had one facet, about 65 per cent had two facets, and only 1 per cent had three or more facets. Typically two facets meet at a sharp ridge or keel that trends northwest to north-northwest (Fig. 3). The undersides of the stones are rounded and slightly weathered. The mineral grains cut by the facets are fresh and have a smooth frosted appearance. Differential removal of relatively soft feldspars and mafic minerals has left quartz, garnet, and other resistant minerals standing in high relief in some cases.

The facets on the east sides of the stones are larger and apparently represent erosion of more rock than was worn away on the west side. The surfaces facing east are usually concave, whereas most surfaces facing west are only slight modifications of the original form of the stones as they were shaped by running water, commonly amounting to little more than removal of the weathered surface.

The stones were studied in the laboratory by means of an improvised goniometer consisting of a box with an open side and horizontal open graduated circle on the top, in which the stones could be oriented as they were *in situ*. A protractor fitted with a level bubble and a radial arm with a perpendicular shoe made it possible to read the azimuths and plunges of the poles of the facets. Instrumental error was of the order of ±3° and the personal error in judgment of facets, many of which were curved, may have been as great as 10° to 15°.

The orientations of the keels of the ventifacts are plotted on a rose diagram (Fig. 4(a)) which shows a strongly preferred trend between northwest and north-northwest. The poles of the facets of the ventifacts on the nearly horizontal ridge crest (Fig. 4 (b)) are concentrated in a belt trending west-southwest, and have a mean azimuth of about 75° and plunge at 55° to 60°. The poles of the facets on ventifacts found on the northern slope (Fig. 4 (c)) show a greater scatter than the first group; the trend of poles is about the same but the mean plunge is nearly vertical. The greater scatter of poles probably is due to the relatively small size of sample. It could result partly from undermining and rolling of the stones; a greater number of facets might be produced by this process, but the "over-edge" ventifacts do not differ from the others. Because of the coarse grain size and the permeable nature of the sand, it seems unlikely that disruption by frost action is responsible for the dispersion of the poles.

THE SAND

The cutting of facets by sand-blasting depends on the volume and velocity of movement of the sand by the wind. The Charette sand is coarse grained and has a large range in grain size compared with other wind-blown sands. Although all of it can be put into motion by high-velocity

(a) Azimuths of keels on 248 ventifacts. Radius of circle represents 20 keels.

(b) Poles of 199 facets of ventifacts on the nearly horizontal part of the ridge crest.

(c) Poles of 81 facets of ventifacts on the north slope of the ridge.
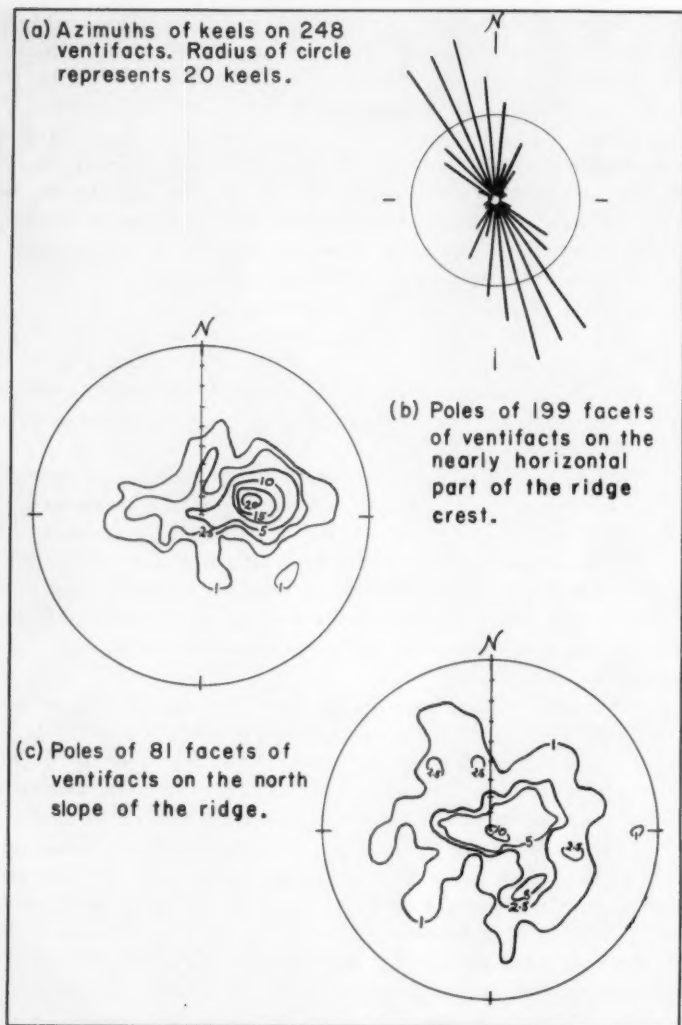
FIGURE 4. Orientation of keels and facets of Charette ventifacts; (b) and (c) prepared from polar plots on upper hemisphere. Contours are in percentages as indicated.

winds (of over 30 miles per hour), only part of it is moved by winds in the range of 10 to 20 miles per hour, and as a result small sand ridges comprising the coarser grain sizes are formed when winds die down. These are close to the sand source, whereas the smaller grain sizes are transported farther and form dunes.

FIGURE 5. Grain-size distribution of Charette sand. Blown sand envelope is based on 17 samples; driven sand envelope is based on 4 samples from sand ridges.

Envelopes showing the grain-size distribution of the sands are shown in Figure 5. The finer of the sands is here termed "blown sand" and moves chiefly by saltation. Saltation is enhanced by the presence of the larger grains which cause a greater rebound of the smaller grains (1, pp. 35–7). The median grain size of the sand decreases from about 0.5 mm. near the ventifact site to about 0.4 mm. in t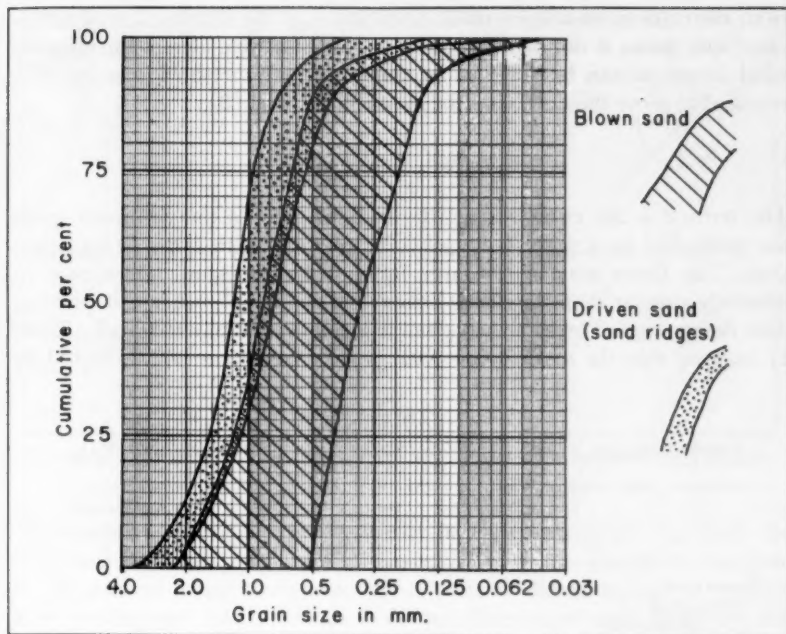he distal part of the most recent sand dune. The median grain size of the sand in the ridges averages 1.0 mm. and the diameter ranges from about 3.0 to 0.125 mm., more than 90 per cent being larger than 0.4 mm. All the sand is well sorted, the sorting coefficients ranging from 1.27 to 1.55 and averaging 1.37.

The presence of the large grains (granules) in the area of the ventifacts causes the smaller grains to bounce rather than "splash" on impact after saltation and gives them a much higher trajectory (1, Fig. 10), probably increasing its altitude tenfold. This must raise the characteristic paths of the saltating grains to such a height that they are not affected by stones projecting less than at least 5 cm. above the ground. Lower stones, such as the Charette ventifacts, could not split the sand flow and cause facets to be cut on two sides of a keel.

The relatively wide range of sand grain size and great distance of Charette

from meteorological stations make calculations of the vectors of sand movement speculative if not delusive. However, a reasonable idea of the effective wind directions can be obtained by computing the threshold velocity (V_t) required to move the sand after the manner of Finkel (8):

$$V_t = 680\sqrt{d}\cdot\log(30/d).$$

The term d is the effective particle diameter; this is the dominant grain size multiplied by a shape factor of 0.75, determined by Bagnold for desert sand. This factor may be too large for the Charette sand, which owes its relatively angular shape to glacial action, and is probably much less spherical than desert sand. Threshold velocities calculated for Charette sands (Table I) indicate that the sand in the distal part of the dunes can be moved by

TABLE I

GRAIN SIZES AND THRESHOLD VELOCITIES OF SAND AT THE CHARETTE, P.Q., VENTIFACT LOCALITY

	Measured grain size (mm.)	Effective particle diameter (mm.) (factor 0.75)	Computed threshold wind velocity (m.p.h.)
Blown sand			
Average of 17 samples			
Median	0.51	0.38	17.7
Smallest quartile	0.36	0.27	7.7
Average of 3 samples in distal part of dune			
Median	0.38	0.28	7.7
Driven sand			
Average of 4 samples			
Median	1.00	0.75	19.4
Smallest quartile	0.76	0.57	18.0

winds of 8 miles per hour. However, most of this sand is on the edge of or in the wooded area and ordinarily the trees interfere with winds so that velocities above 8 miles per hour may be required once the sand has been deposited there. The calculations suggest that winds in excess of 18 miles per hour are required to move the sand enclosing the ventifacts. If some allowance is made for the unknown error in shape factor, the complexities of movement of sand containing several grades of grain size, and the remoteness of meteorological stations, the threshold wind velocity might be reduced to about 15 miles per hour.

THE WINDS

Wind data are available for Montreal (Dorval airport), Quebec city, and for short periods for St. Hubert and Duchesnay (3). The monthly data have been recomputed as average annual percentage frequency by
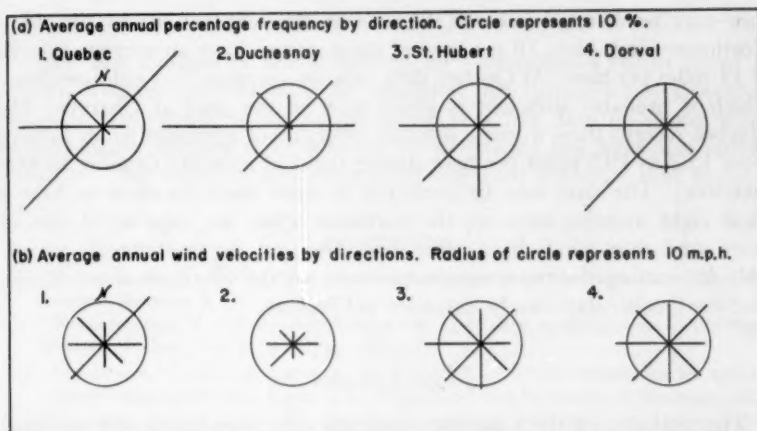
FIGURE 6. Rose diagrams showing average annual winds for meteorological stations in the St. Lawrence Lowlands.

direction and average annual velocity by direction (Fig. 6). Had the stations been closer to Charette, it would have been feasible to compute the theoretical amount of sand flow in various directions and to prepare a vector diagram that would show the net direction of sand transport, but this may be less important than wind velocity in the cutting of ventifacts.

From Figure 6 it is clear that the prevailing winds in the St. Lawrence Lowlands are from the west and southwest; together these winds blow about 45 per cent of the time. Their average velocity is about 10.5 miles per hour, which is sufficient to move the small size-fraction of the Charette sand. This is about a third of the sand by volume.

Winds from the northwest to north sector or from the south to southeast sector are responsible for the keels and facets *if* Walther's wind-splitting theory is valid. Their frequencies and velocities are given in Table II.

TABLE II

Wind	Frequency (per cent)	Average velocity (m.p.h.)
Northwest to north	16	7.5
Southeast to south	13	7

Clearly these winds are relatively ineffective in forming ventifacts at Charette, and Walther's theory does not apply at this locality.

Winds from the northeast and east blow 26 per cent of the time and have an average velocity of 9 miles per hour. As is apparent from Figure 2, the ventifact locality is shielded from east winds by the high part of the ridge. However, northeast winds have an unimpeded approach, though

they may be diverted towards the west at the ventifact site by the ridge. Northeast winds blow 18 per cent of the time and have an average velocity of 11 miles per hour. At Quebec their velocity averages 15.5 miles per hour, which is probably sufficient to move most of the sand at Charette. The Quebec records show average monthly velocities of northeast winds ranging from 15.2 to 19.5 miles per hour during the cold months (October to May inclusive). The sand may be protected by snow cover for three or four of these eight months; even so, the northeast winds are capable of moving more sand than winds from other directions and are undoubtedly responsible for cutting the most significant facets on the ventifacts if we assume that the Quebec data can be extended to Charette.

Conclusions

The majority of the Charette ventifacts have two facets and one keel. One facet is shallow, or amounts to little more than a polish of the parts of the stones facing west. It was formed by the prevailing west to southwest winds, which are strong enough to move only about a third of the Charette sand in terms of grain sizes. The other facet is deeply cut and faces eastward. It has been cut by the relatively high-velocity northeast winds that blow during the cold season; such sand-blasting is probably important during the snow-free parts of March, April, May, October, and November. Bottles emplaced in the sand showed appreciable frosting after 18 months. We conclude that the ventifacts have been formed by winds having a pattern similar to the present one over an unknown period, possibly of the order of several hundred years. These ventifacts may be quite recent, and no special conditions such as the northeast winds postulated by Terasmae and Mott (14) to explain the orientation and morphology of sand dunes near Prescott, Ontario, are necessary at Charette.

The keels of the Charette ventifacts trend north-northwest but the winds to and from this direction are too weak to move any but the finest fraction of the Charette sand. From this and the asymmetry of the facets we conclude that Walther's theory of the splitting of sand flow by ventifacts does not apply here. Rather, the facets form transverse to the effective wind direction by the impact of saltating grains which break out microscopic fragments and produce a frosted or polished surface.

Note Added in Proof

Since this manuscript was submitted for publication a recent paper by
Ph. H. Kuenen (16) came to our attention. Kuenen shows by laboratory
methods that ventifacts can be produced in a few days by strong winds
moving coarse angular sand, whereas winds moving fine sand may require
centuries. The Charette ventifacts constitute field evidence that supports
his view.

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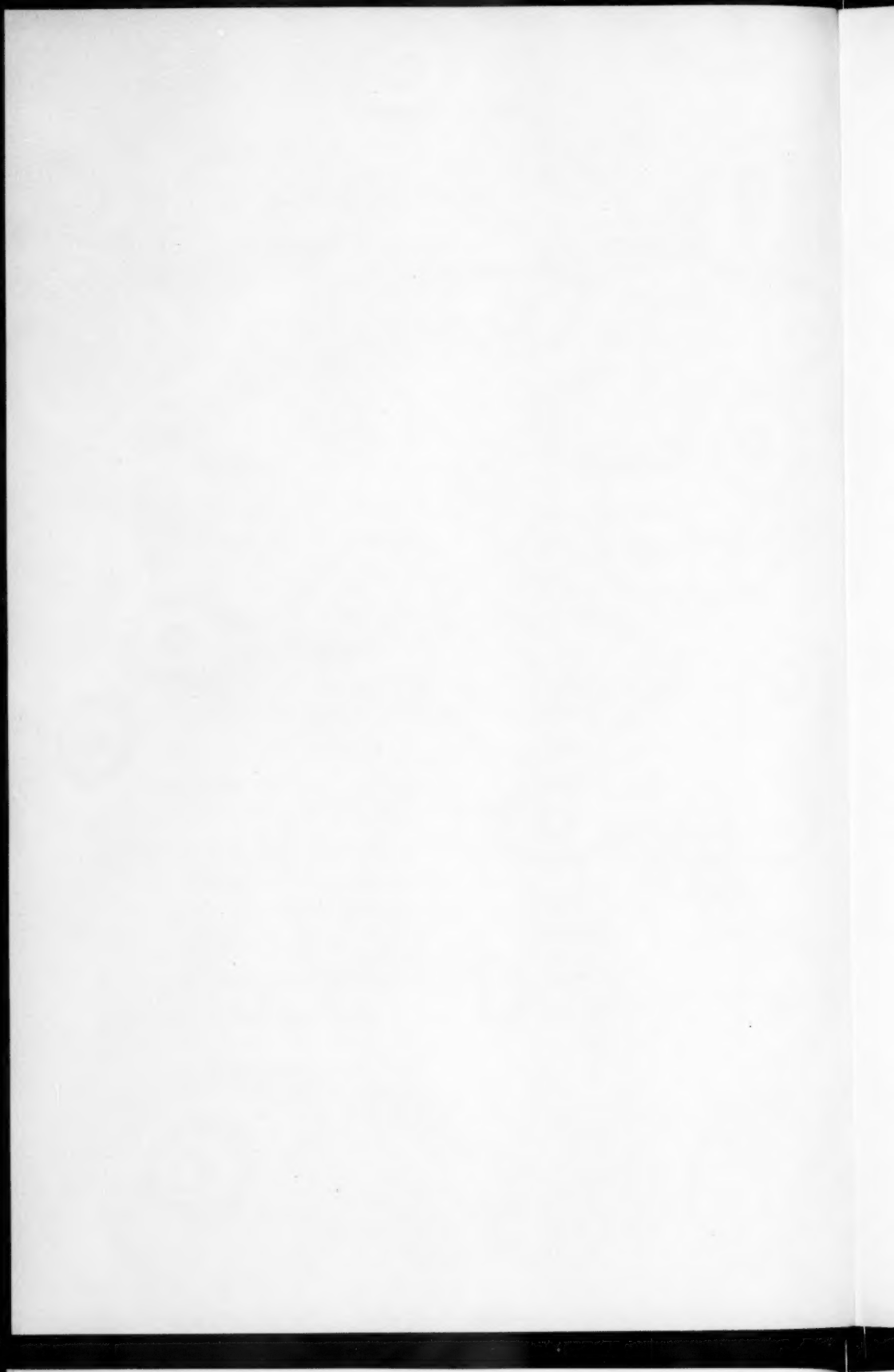
Bolboporites americanus in the Chazy of Southern Quebec

T. H. CLARK, F.R.S.C., AND H. J. HOFMANN

ABSTRACT

A study of over 250 specimens of *Bolboporites americanus* Billings from the Chazy group of southern Quebec has produced new information on the character of this fossil. In any one locality it occurs in a variety of shapes ranging between prolate, globular, and conical end members. The fossils are interpreted as specialized spines of cystids, possibly of the hydrophorid *Palaeocystites tenuiradiatus* (Hall), with which they are usually associated. A correlation between the shape of the spine and position on the calyx is suggested.

FOR over one hundred years *Bolboporites americanus* has been known to occur in abundance within the Chazy group of the Lake Champlain and St. Lawrence Lowlands. Ever since it was first described it has been considered a curious or peculiar fossil by those few investigators who have had occasion to examine it, and we are no exception. The purpose of this paper is to present the results of a study of more than 250 specimens from the Chazy of southern Quebec, and to fix attention on this little-understood fossil. The investigation was initiated and supervised by the senior author. The actual study and interpretations, and the preparation of the paper, were the responsibility of the junior author.

Although the fossil is abundant locally, good specimens are rare. Heavily weathered calcarenite and shale beds are the best collecting grounds; massive, and freshly fractured calcarenites almost never show a recognizable individual. For this reason the determination of the subsurface distribution of *Bolboporites americanus* is a difficult task that still remains to be accomplished.

The study material comprises 90 specimens from the Redpath Museum of McGill University, about 45 from the study collection of the Department of Geological Sciences, McGill University, 30 from the collections made by the senior author for the Quebec Department of Mines, and about 80 individuals collected by the junior author in 1960. In addition, the United States National Museum loaned for examination all 33 specimens of *Bolboporites* in their collections, 15 of which belong to European species. Hall's and Ruedemann's types were kindly provided by the New York State Museum.

We are much indebted to the officers of these institutions who sent the type and other specimens: Mrs. Alice J. Turnham and Mrs. J. S. Stevenson

of the Redpath Museum, Dr. P. M. Kier and Dr. G. A. Cooper of the United States National Museum, and C. F. Kilfoyle of the New York State Museum. We also wish to thank Professor Gerhard Regnéll of Lund University, Sweden, for written discussions and for sending a copy of an unpublished manuscript. Dr. R. H. Flower, of the New Mexico Institute of Mining and Technology, and Dr. L. F. Hintze, of Brigham Young University, provided information concerning the occurrence of the genus. Dr. T. E. Bolton, Curator of the palaeontology type collections of the Geological Survey of Canada, gave permission to examine the type material.

HISTORICAL

The genus was established by Pander (29, p. 106) on material from the Ordovician of the Leningrad region, U.S.S.R.

James Hall (18, p. 18, Pl. 4, Fig. 7a–d), in his classic work *Paleontology of New York*, vol. I, was the first to mention and illustrate a North American representative of the genus. Yet he did not recognize it as such for he assigned it to the coral *Chaetetes*, species undetermined. Hall pictured this fossil at least two more times, in Figures 8 and 9 on the same plate, under *Actinocrinus tenuiradiatus*, which he shows as aggregates of plates. His comment on *Chaetetes* sp. is as follows (p. 18): "Small rolled masses, in the shape of acorns or eggs, are common among the crinoidal plates in the Encrinal limestone at Chazy."

Billings (5) was the first to identify *Bolboporites* as such in the Chazy of Mingan and Montreal, and called it *Bolboporites americana* (p. 381). A description and four figures of this species appear on pages 429–30 of his paper. He thought it was a zoophyte.

In Logan's *Geology of Canada* (24, p. 125) the four figures by Billings are reproduced, and it is stated that "it is classed by Salter as a coral, but it presents the same crystalline peculiarity as the crinoids and the cystideans."

Chapman (11, p. 195) pictured *Bolboporites americanus* and referred to it as "a peculiar form of uncertain character." The same study also appeared in book form in 1864, 1871, and 1883.

Miller (25, p. 174, Fig. 140) gave Billings' original figures and said it was probably a coral, whereas he considered the genotype (*B. mitralis*) to belong to the Echinodermata.

Ami (1) produced faunal lists for southern Quebec localities, and suggested (p. 121) that *B. americanus* "is probably a portion of the interior of one of the cystoidea so prevalent in these rocks [Chazy]."

Occurrences and distribution of *B. americanus* were described by Brainerd and Seely (7; 8), Brainerd (6), White (39), Ruedemann (36), Raymond (31; 32; 33), Twenhofel (37), Clark (12; 13), and Oxley and Kay (28). Bassler (2, p. 128) published a synonymy of this fossil.

Bolboporites americanus occupies an "uncertain" or "doubtful" taxonomic position in the systematic treatises on echinoderms by Bassler (3,

p. 53), Brighton (9, p. 30), Bassler and Moodey (4, p. 336), and Moore and Laudon (27, p. 103).

The fossil is not mentioned in modern American textbooks on palaeontology.

GENERIC CHARACTERISTICS

The name *Bolboporites* is applied to small bodies of calcite, in the form of a smooth, flat to globular base, surmounted by a celluliferous projection that may be conical to hemispherical in shape. A small double-winged depression is located on the base either at the centre or towards one side. The size of the fossils ranges from a few millimetres to about 15 millimetres in length, and a little less in width. In thin sections one can observe an eccentric axial structure which terminates at the base in a little opening situated between the two wings of the basal depression, and pinches out apicad before reaching the apex of the cone. A three-dimensional lattice-like microstructure is discernible in some specimens, and the compartments of this meshwork have an edge length of approximately 20 microns. As far as the writers know, *Bolboporites* has thus far been found only in the Ordovician of northern Europe and eastern North America. Important references concerning the genus are listed at the end of the paper. Genotype: *Bolboporites mitralis* Pander 1830.

Bolboporites americanus BILLINGS

Chaetetes sp. Hall 1847, *Pal. New York*, vol. 1, p. 18, Pl. 4, Fig. 7a–d.

Bolboporites americanus Billings 1859, *Can. Nat. and Geol.*, vol. 4, pp. 429–30, Figs. 3–6.

    Logan 1863, *Geol. Can.*, p. 124, Fig. 44a–d.

    Chapman 1863, *Can. J. Sci. and Arts*, n.s. vol. 8, no. 45, p. 195, Fig. 165b.

    Miller 1889, *N. Am. Geol. and Pal.*, p. 174, Fig. 140.

    Ruedemann 1901, N.Y. State Mus., Bull. no. 49, p. 11, Pl. 1, Fig. 1. (This may be a different species.)

    Twenhofel 1938, Geol. Soc. Amer., Special Paper 11, p. 42.

[non] *Bolboporites americanus*? Butts 1941, Virginia Geol. Surv., Bull. no. 52, pt. 2, Pl. 95, Fig. 34.

No holotype seems to have been designated. The cotypes are in the collections of the Geological Survey of Canada (nos. 1013, a–e), and were collected on the Island of Montreal.

Morphology

Billings' original description is as follows:

These curious little fossils consist of a smooth solid hemispherical base surmounted by a conical projection which is celluliferous, the cells being about the size and shape of those of the common *Stenopora fibrosa*. In the centre of the base there is a small pit which appears to have been the point of attach-

ment. The solid part, under the hammer, usually breaks up into rhomboidal fragments, but some specimens when fractured exhibit a prismatic structure, the prisms radiating from the centre and being about the size of the tubes in the celluliferous conical extremity. It is remarkable that the cells slope down-
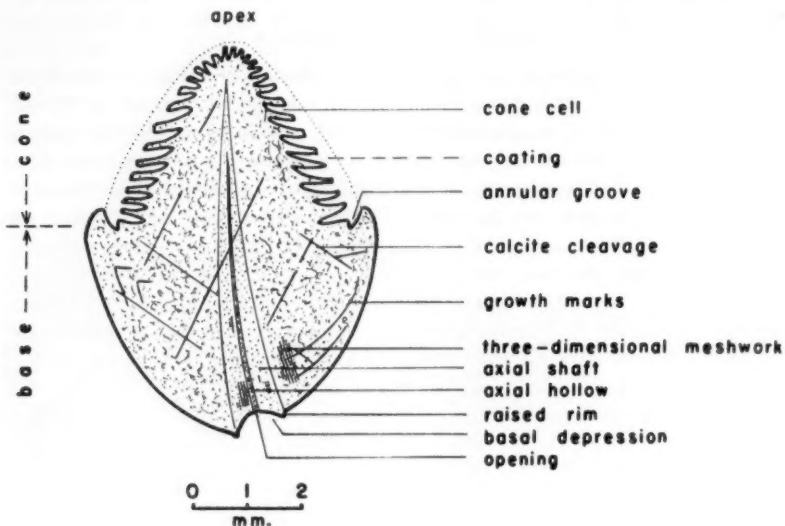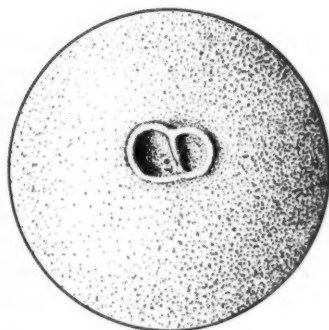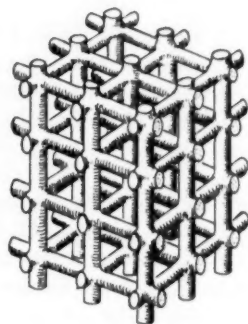

Diagram of longitudinal section in plane of symmetry.

Bottom view.

Three-dimensional meshwork.
(interpretation)

FIGURE 1. Morphological features observed in *Bolboporites americanus* Billings.

wards instead of upwards as in all other zoophytes, and it is possible that the apex of the cone is the base: the greater size and solidity of the hemispheric extremity, however, would seem to favour the opposite conclusion.

The specimens are from three to eight lines in length, and about the same in greatest diameter. The cone is usually of the same height as the hemisphere, but sometimes it is either shorter or longer.

Much additional information has been gained during the present study of material from outcrops and quarries in the Montreal region. The morphological features of the specimens examined are shown in Figure 1.

The fossil is composed of a smooth base with a basal depression and opening, and a cell-bearing cone. In certain of the larger and better-preserved (i.e., well-weathered) specimens there is a groove along the bottom of the cone, which appears as if it has been a place of attachment for some soft part (coating?) of the body (Fig. 2, no. 11). A number of individuals from shale beds do not show the cells (Fig. 2, no. 10). Instead, the surface is smooth, and it is difficult to distinguish between base and cone; their appearance is that of a short spine.

The small pit that Billings mentions is actually, in good samples, a double-winged depression surrounded by a narrow raised rim, the structure having an outline similar to the number 8. It is about 1.2 mm. by 2.0 mm. across, and 0.4 to 0.7 mm. in depth. A small opening is located in the middle, but is normally obscured by weathering or detritus. The position of this basal depression is usually close to the centre in prolate forms, but in the larger specimens, and in those with a high value for the ratio of basal diameter to total length, it is displaced upward and sideways, as much as halfway to the cone. The orientation in this eccentric position is such that the long diameter of the 8 is bisected by a vertical plane of bilateral symmetry.

The cone cells slope downwards over most of the cone surface, except at the apex and, rarely, at the bottom of the cone. They are circular to elliptical or slightly angular in cross-section, and range in diameter from 0.2 to 0.4 mm. and are smallest at the apex. They may be shallow pits or may taper to a point about 0.8 mm. deep into the cone. For any particular specimen there are from 80 to over 200 cells and their arrangement is irregular, or regular over part of the cone surface (Fig. 2, nos. 1, 7, 9). Thin walls separate the cells from one another.

A few fragments of the basal part of the fossils show the prismatic structure (Fig. 2, no. 6) to which Billings referred. On close examination this structure is found to be due to closely spaced intersecting calcite cleavage faces, the orientation of each of the crystals being slightly different from that of its neighbour.

Fractured specimens exhibit a pointed greyish axial region originating at the basal depression and pinching out just inside the apical portion. It is curved when the depression is eccentrically located. In thin section this structure is seen to be composed of an axial hollow (filled with quartz silt detritus), and an axial shaft made up of flesh-coloured calcite that is
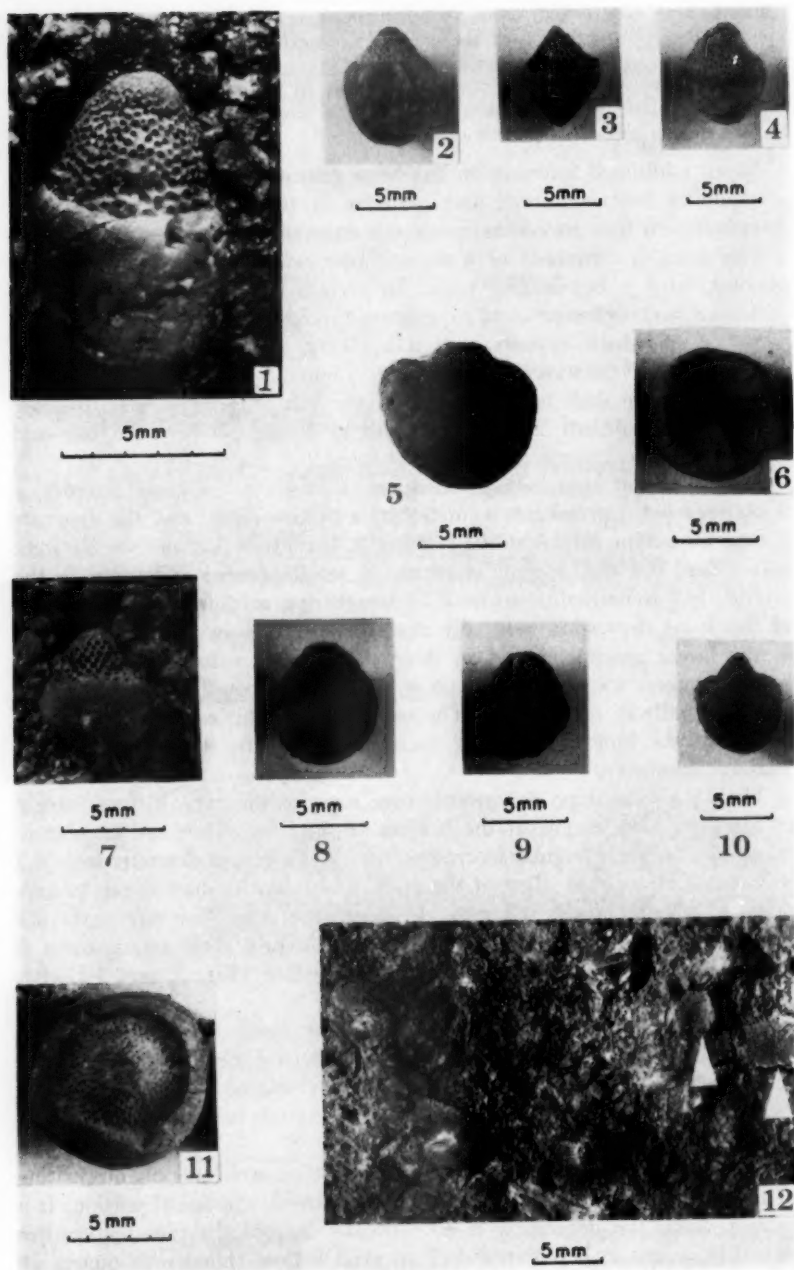
FIGURE 2

distinctly less cloudy than that of the rest of the body. In several slides there are faint dark lines subparallel to the bottom of the cone or the basal surface, which may be growth marks.

The smallest structure recognizable in thin section is a three-dimensional meshwork filled with an opaque substance. Dimensions of the edges of the resulting compartments are approximately 17 microns at the base, and smaller towards the apex. The material in the collections is not sufficiently well preserved to show whether their form is cubic, rhombohedral, or something else. This microstructure was observed only close to, and in the axial region, and it greatly resembles that found in spines of modern echinoids, such as *Heterocentrotus*.

The optical orientation of the calcite in specimens having good single-crystal structure differs from one individual to the next. The c-axis is at a variable angle to the axis of the fossil. There are two well-developed cleavage faces on fractured individuals, one being more inclined to the fossil axis than the other. A third cleavage direction is not pronounced.

In several localities, where it occurs in coarsely crystalline calcarenite, *Bolboporites americanus* has a pink colour, the same as associated cystid or bryozoan fragments. An X-ray fluorescence examination showed the presence of manganese in the crystal structure and this may be responsible for the colouration. The substitution of manganese for calcium is a post-depositional feature.

The total length (L) of the specimens measured lies between 4.5 and 11.5 mm., and the base length (B) ranges between 1.0 and 7.3 mm. The

FIGURE 2. 1. *Bolboporites americanus* Billings. Side view of a large prolate specimen showing calcite cleavage on base, narrow annular groove, and disposition of the cone cells. Chazy group, L'Abord-à-Plouffe, Ile Jésus, Quebec. Redpath Mus. coll. no. 2.364. 2. *Bolboporites americanus* Billings. Side view of a specimen with annular groove, long base. Chazy group, 1.5 miles south of Terrebonne, Quebec. 3. *Bolboporites americanus* Billings. Side view of a rare specimen with conical base. Chazy group, 1.5 miles south of Terrebonne, Quebec. 4. *Bolboporites americanus* Billings. Side view of specimen having measurements similar to those in 3, but extremities are rounded. Chazy group, 1.5 miles south of Terrebonne, Quebec. 5. *Bolboporites americanus* Billings. Specimen with a very large base and deep annular groove. Chazy group, Caughnawaga, Quebec. Redpath Mus. coll. no. 2.355. 6. *Bolboporites americanus* Billings. Top view of a basal fragment with radial structure of calcite crystal faces. Chazy group, Caughnawaga, Quebec. Redpath Mus. coll. no. 2.355. 7. *Bolboporites americanus* Billings. Side view of a specimen with regularly arranged cone cells. Chazy group, L'Abord-à-Plouffe, Ile Jésus, Quebec. Redpath Mus. coll. no. 2.365. 8. *Bolboporites americanus* Billings. Side view of a globular specimen with long base and shale-filled cone cells. Chazy group, Billet quarry, Village Bélanger, Ile Jésus, Quebec. 9. *Bolboporites americanus* Billings. Side view of a specimen lacking annular groove. Chazy group, Caughnawaga, Quebec. Redpath Mus. coll. no. 2.355. 10. *Bolboporites americanus* Billings. Oblique view of a specimen without cone cells. Chazy group, 1.5 miles south of Terrebonne, Quebec. 11. *Bolboporites americanus* Billings. Top view of a large specimen with annular groove. Chazy group, L'Abord-à-Plouffe, Ile Jésus, Quebec. Redpath Mus. coll. no. 2.365. 12. *Palaeocystites tenuiradiatus* (Hall). Weathered slab with scattered thecal plates showing parallel pores. The arrows point to plates showing the smooth inner surface and the notched sutures. Chazy group, Montreal area. Study collection, Department of Geological Sciences, McGill University.

smallest width (base diameter, W) is 3.2 mm., and the greatest 9.2 mm.
Most of the bodies have a circular cross-section, but about one-fifth of
them are slightly elliptical. The maximum and minimum diameters of the
latter have been averaged for plotting purposes. Results of the caliper
measurements on samples from the Montreal region are plotted on the
scatter diagram (Fig. 3). It is evident that most of the bodies are longer
than wide, and also that the base is generally wider than it is long.
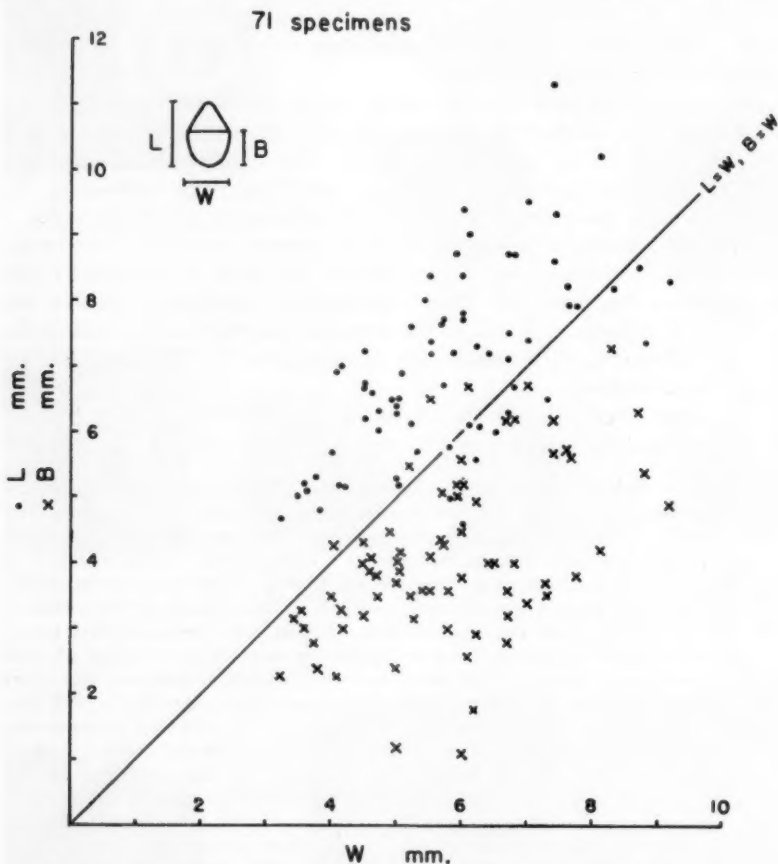
FIGURE 3. Scatter plot of total length/width (●) and base length/width (×).

Variations in shape are considerable, and can best be seen by consulting
Figure 4, which was developed expressly for the presentation of data on
Bolboporites americanus. The numerical data obtained by caliper measure-
ments of the three variables L, B, and W were transformed into a three-
ratio plot. The W/L ratio is plotted against B/W. Superimposed on this
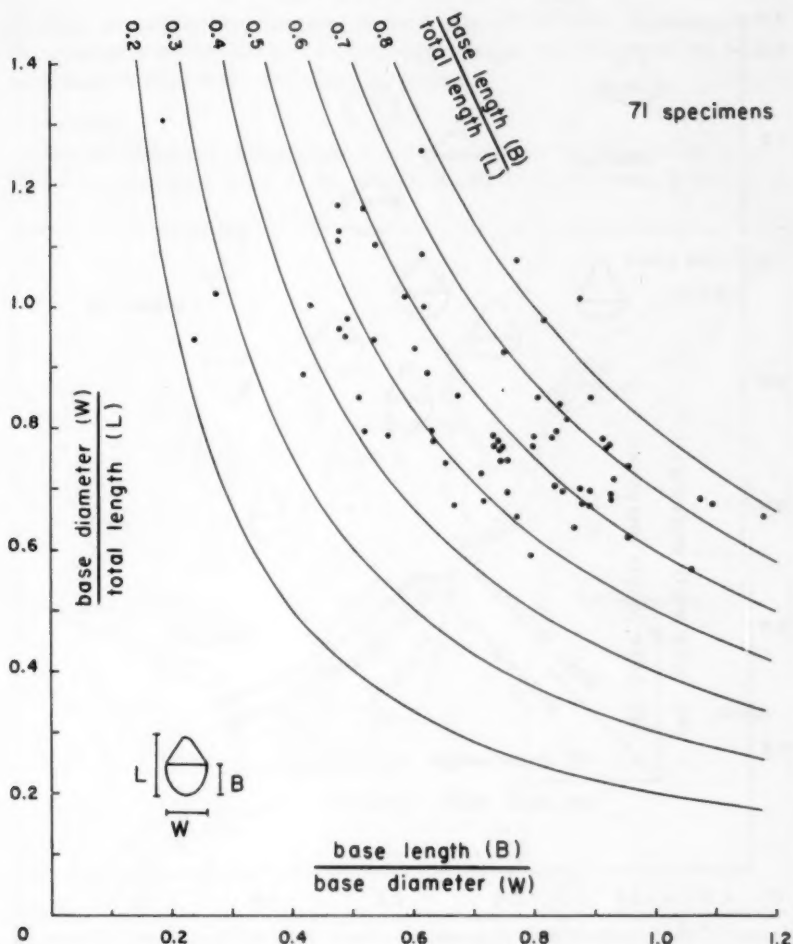
FIGURE 4. Shape analysis of *Bolboporites americanus* from southern Quebec. Scatter diagram showing variations in shape by three-ratio plot.

graph are the related B/L curves. On the resulting diagram the three ratios (i.e., shape) can be read off directly, and the frequency of any particular shape is indicated by the closeness and number of dots. To facilitate the visualization, a pictograph drawn on the same scale is added (Figure 5). The vectors in the diagram indicate the variation of a quantity with respect to total length as one goes from one shape to an adjoining one. As can be seen, the shapes vary continuously over a wide range between three arbitrarily designated end members: conical, globular, and prolate.

Not much would be gained by proposing an elaborate classification of
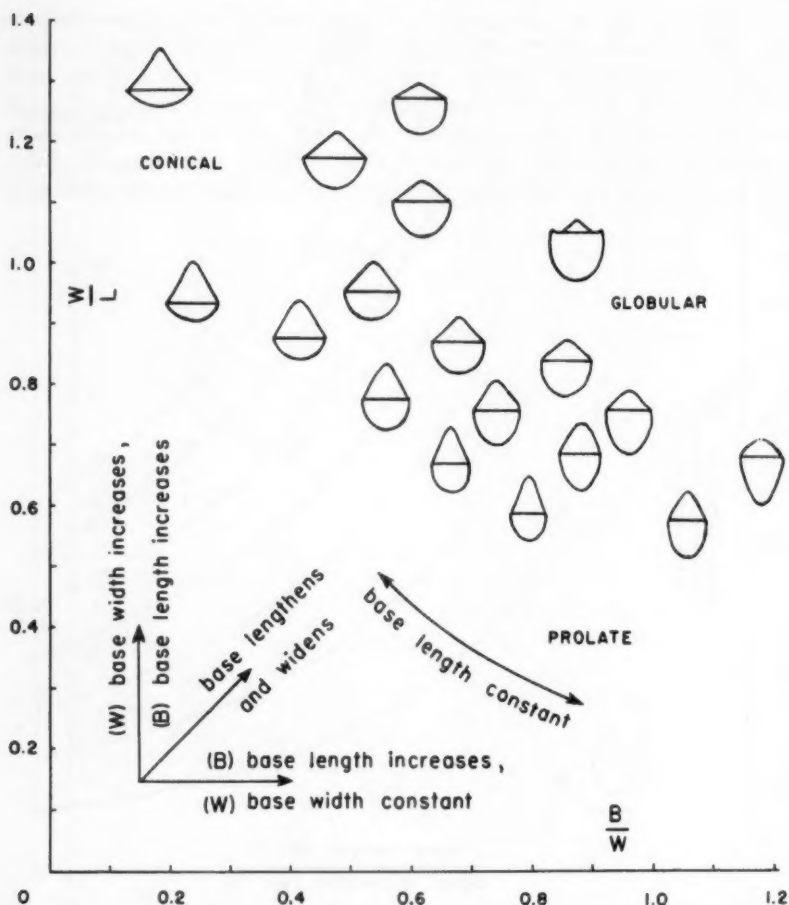
FIGURE 5. Shape analysis of *Bolboporites americanus* from southern Quebec. Pictograph showing variations in shape.

the forms based on arbitrary limits. Strictly, the three-ratio scatter plot is inadequate in expressing the degree of curvature of the surface. However, it does give an idea of the relative proportions of base and cone. On Figure 4 most of the European forms would fall in the top left corner of the field, because the base length is generally short.

The continuous variation of shape within a certain range is of significance and bears on the problem of the character of this fossil. A study was made by plotting the measurements and derived ratios according to occurrence in lithology, and according to their geographic and stratigraphic positions, but no significant trends were obvious. This may be due to the small

number of satisfactory samples. A good example of lack of association is demonstrated by the samples from Caughnawaga, which showed the widest variations, from conical to globular to prolate.

Occurrence

The geographical distribution is given on Figure 6. *Bolboporites americanus* is a common fossil in the Chazy of the Montreal area. It occurs in

FIGURE 6. Map showing occurrences of *Bolboporites americanus*. Other occurrences: Mingan Islands, Quebec; Rysedorph Hill, New York.

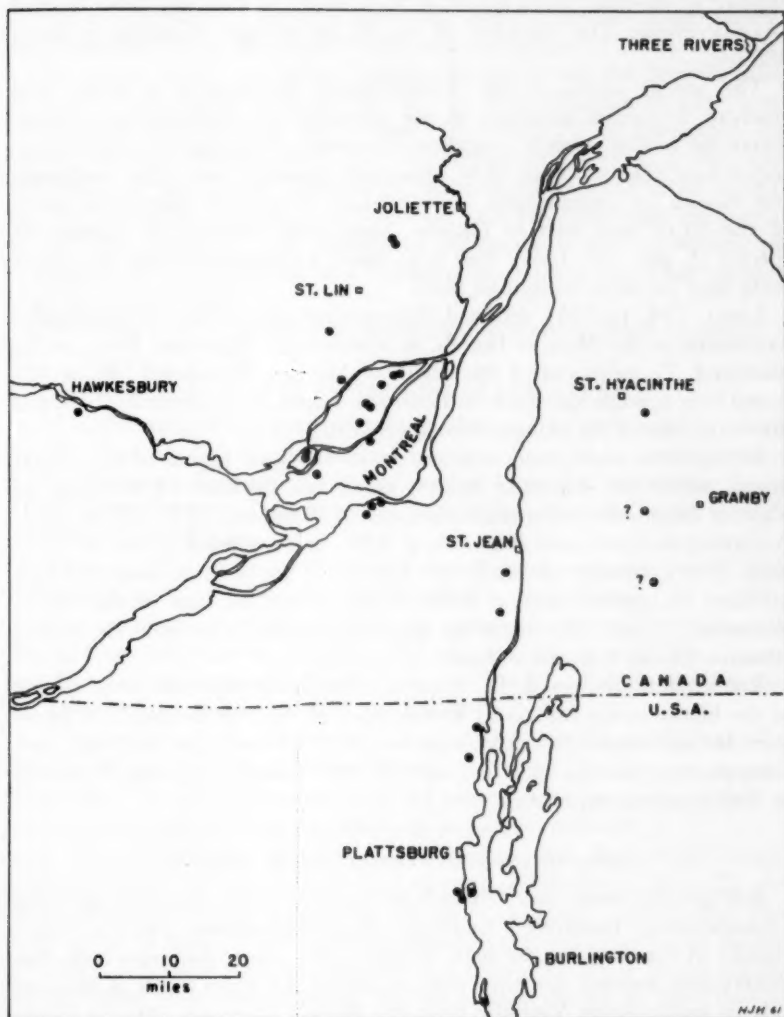shaly beds as well as in the coarse-grained calcarenites composed mainly of crystallized echinoderm remains. The species covers a considerable strati-graphic interval, but the exact amount cannot be determined because there is no complete surface section in this region. However, a minimum of 110 feet is indicated in the St. Martin area on Ile Jésus (Lagacé quarry). No specimens were found in the topmost part of the Chazy, 24 feet of which are exposed in the Devito quarry in Pointe Claire. The uppermost 6 feet exposed in the abandoned quarry in St. Vincent de Paul also failed to yield any specimens. The thickness of the Chazy around Montreal is about 300 feet.

The species occurs on the Trans-Canada Highway in a quarry and road-cut five miles southeast of the cloverleaf at Hawkesbury, Ontario, where the rock is coarsely crystalline calcarenite. The quarries at St. Domi-nique, four miles southeast of St. Hyacinthe, provided only a few fragments, but enough for identification. Two localities 12 and 22 miles to the south of the latter, and west of Granby, have been reported to contain the species (1, pp. 118, 134). This is probably a misidentification, for Chazy rocks have not been recognized there.

Logan (24, p. 134) reported *Bolboporites americanus* in crossbedded calcarenite at the Mingan Islands, in a section at Clearwater Point on the mainland, 27 miles east of the village of Mingan. Twenhofel (37, p. 42) found only a single specimen on Perroquet Island, in an interval 21–46 feet above the base of the Mingan formation (Chazy).

Bolboporites americanus also occurs in the type region of the Chazy group, where the sediments have a maximum thickness of 890 feet, on Valcour Island, five miles south-southeast of Plattsburg, N.Y. (32, p. 526). According to Oxley and Kay (28, p. 820), it is confined to the 200-foot-thick Fleury member of the Lower Chazyan Day Point formation, which occupies an interval starting about 90 feet above the base of the Chazy. Raymond (32, p. 528) found the species to extend 75 feet into the Middle Chazyan Crown Point formation.

Ruedemann (36, pp. 8, 11) made a collection of *Bolboporites* in certain of the blocks in the breccia at Rysedorph Hill, east of Albany, N.Y. How-ever, his specimens (N.Y.S.M. type no. 4877) do not show the base, and, consequently, the species is not certain. The internal structure illustrated by him is more interpretation than fact.

Bolboporites ELSEWHERE IN NORTH AMERICA

Bolboporites americanus? (U.S.N.M. no. 97750) is said to occur in the Chambersburg limestone (Edinburg formation—Lower Middle Ordo-vician) at Strasburg in northern Virginia (10). Five specimens from that locality and another specimen from a locality 1.5 miles south of Hanson-ville in southwestern Virginia, from the Benbolt limestone (Middle Ordo-vician), were kindly loaned by the United States National Museum. Only one of the samples (U.S.N.M. no. 139457) from the Strasburg area

resembles the forms of the typical Chazy in that it has a comparatively large base. Yet it is larger and has oval cone cells that are arranged in vertical rows. Its measurements are: $L = 11.0$ mm., $B = 3.7$ mm., $W = 9.4$ mm.

The other five Virginia specimens resemble each other, and look more like small specimens of the European species. Instead of a globular base, they have a smooth oval base with an axis of curvature that is perpendicular to the plane of bilateral symmetry, and the double-winged depression is located close to the periphery of the basal surface.

The lower part of the Chambersburg limestone and the Benbolt limestone were considered by Kay (20, p. 95) to be Bolarian in age (post-Chazy, pre-Trenton), and by Cooper (14, Chart 1), of Porterfield age (post-Chazy, pre-Black River). This was revised by Kay (21, p. 94), who put the lower part of the "Porterfield" stage of the Bolarian series equivalent to the upper Chazyan (Valcourian), and the upper part equivalent to the Black Riveran. This problem of correlation is still not solved, but apparently the fossils belong to a stratigraphic horizon somewhat younger than the typical Chazy.

The genus has so far not been recognized in western North America.

NOTES ON THE CHARACTER OF THE FOSSILS

As was mentioned in a previous section, *Bolboporites americanus* has been variously regarded as a coral, bryozoan, echinoderm, or as an unclassified fossil. The most favoured interpretation has been that it belongs to the echinoderms, because of its close association with crinoid and cystid remains and its crystallized form.

Among palaeontologists who studied the European species several other interpretations were advanced. Milne-Edwards and Haime (26, p. 246) found a resemblance to the dactylopores and considered them to belong to the foraminifera, whereas Pander, who also saw this resemblance, classed the dactylopores as corals. Von Wöhrmann (*in* 19) thought *Bolboporites* to be parts of the thecal plates of *Cheirocrinus*.

A detailed study of the three-dimensional microstructure led Yakovlev (40) to believe that *Bolboporites* was related to the Hydrozoa or Stromatoporoidea. He also commented (p. 9) that it must be characterized as being unattached and as having the apex pointing downward.

A year before that, Wanner (38) suggested that *Bolboporites* bodies represent spines of some echinoid. Following Lindström (23, p. 7), the spine theory was taken up again by Eltysheva (17), who thought that they were spines of an asteroid, similar to the conical protrusions on the Recent *Oreaster*. Echinoids and asteroids are not known to occur in the Chazy, so that these two interpretations find no support as far as the Chazyan species is concerned. On the other hand, cystids, and to some extent crinoids, are very abundant and, if the forms represent spines, they more likely would belong to a class of the Pelmatozoa.

Regnéll (34; 35, p. 81; and written communication, 1960) is of the opinion that there is a connection between *Bolboporites* and the hydrophorid genus *Cheirocrinus*.

The puzzle is unlikely to be solved completely until specimens are found which indicate the nature of the bodies attached to the basal depression or to the cone cells. In this respect the present investigation was unsuccessful. Nevertheless, it was noted that in the Montreal region bodies of *Bolboporites americanus* usually, though not always, occur together with plates of *Palaeocystites tenuiradiatus* (Hall), with *Cheirocrinus forbesi* (Billings) present in a few places too. Raymond (32, p. 528) found no consistent association on Valcour Island, but Ruedemann collected *Bolboporites* and *Palaeocystites* together at Rysedorph Hill near Albany, N.Y. Hall (18, Pl. 4, Figs. 8, 9) figured the association without apparently realizing the significance of it.

The character of the material from southern Quebec leads one to conclude that *Bolboporites* is part of a cystid rather than a single organism or a colony. One of the problems now is to establish whether the bodies are external (such as highly specialized spines), part of the theca, or internal structures. The specimens provided nothing to indicate that the body is part of a thecal plate.

Arguments for the spine theory are based mainly on the presence of the basal depression which is explained as an articulating device, and on the superficial resemblance to some modern echinoderm spines. Difficulties are encountered in trying to account for the double-sided concavity, which does not occur in modern echinoderms. The depression can perhaps be considered as having functioned as a hinge joint by restricting the mobility to one plane and permitting up and down movements of the spines. One could explain the orientation of the depression with respect to the bilateral plane of symmetry, in specimens with eccentric basal depression, by considering the bodies to have come from different parts of the animal. The ones with eccentric hinge joints would probably be situated towards the bottom and would be large; the ones towards the top would be smaller and prolate in shape. This speculation is in agreement with the variety of shapes present in any one locality. The bodies would be detached soon after death, and this may account for the lack of attached specimens. The thecal plates of *Palaeocystites* and *Cheirocrinus* found in the Montreal region have about the size required to accommodate such spines. However, no hinge joint tubercle was observed in any of several fairly complete specimens of *Cheirocrinus forbesi* (Billings). Plates of *Palaeocystites* have a flat cone shape. They might have supported a spine, though the plates are too much weathered to permit one to be certain that the apex of the cone is actually double-sided. With this theory the function of the cone cells on a spine still remains unexplained.

Another possible interpretation should be considered briefly, namely, that of an internal organ. Whereas Billings originally compared the size and

shape of the cone cells with the zooecia of a bryozoan, it is perhaps more significant to make a comparison between the cells and the thecal pores of *Palaeocystites* which belongs to the hydrophorid order Rhombifera (Fig. 2, no. 12). A similarity is readily seen. The number of pores in any one animal must be large. As no complete specimen of *Palaeocystites* was examined, the actual number can only be guessed. The number of cone cells is also large (80 to 200 or more). If the structure occupied an internal position, it could perhaps have served in the respiratory process in some way. One of the difficulties here is to interpret the double-winged basal depression, especially when it is eccentrically situated. This interpretation of internal position should be easy to prove or disprove when complete specimens of *Palaeocystites* are available for sectioning.

In conclusion, it may be said that from a consideration of the present evidence it seems more likely that the bodies referred to *Bolboporites* from the Chazy of southern Quebec represent external organs, such as specialized spines of cystids, possibly of *Palaeocystites tenuiradiatus*. Both fossils are excellent indexes for the Chazy group in this region.

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Complex Folding and Associated Minor Structures on Reno and Waldie Mountains, Southeastern British Columbia

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ABSTRACT

Complex disharmonic folding in a series of dolomites, limestones, and argillites, on the west side of the Sheep Creek anticline, is illustrated by means of a series of cross-sections. The distribution of cleavage, drag-folding, and other minor structures with respect to the major structures is discussed.

THIS paper presents some structural conclusions derived from two summers of mapping in the Selkirk Mountains, in the vicinity of the settlement of Sheep Creek, south of Nelson. The field work was done in connection with an exploration project of the American Metal Company. C. V. G. Phipps, S. S. Alderman, and L. Jacobs were associated with the writer in the mapping. Dooley P. Wheeler initiated and directed the programme. Permission to use this information is gratefully acknowledged.

The area is covered by thick bush, except on the mountain summits; consequently mapping had to be done by traverses, using tape and compass, and tied into the boundaries of surveyed claims. Traverses were spaced at intervals of 150 feet in the surveyed claims, and 300 feet apart in adjoining areas. The area is geologically interesting because of the intense deformation which some of the lithological units have suffered, because of the contrast in degree and type of deformation between various rock types, and because of the evidence of considerable variations in structural facies with changes in structural position.

Mapping was done on a lithological rather than stratigraphic basis, and little reference will be made here to stratigraphic nomenclature, which has been discussed fully by Fyles and Hewlett (1), Little (2), and Matthews (3). The rock types have been assigned by Fyles and Hewlett (1, p. 16ff.) to the Laib formation (Cambrian) and the Active formation (Ordovician). Although not involved in the mapping, the underlying Cambrian Reno and older quartzitic formations, which make up the core of the Sheep Creek anticline, have exerted a controlling influence on the deformation.

The lithological units represented on the map (Fig. 1) are the following:

A: up to three limestone bands and schist; the limestone bands are well exposed only at the north and south extremities of the map.

B: biotite schist, spotted with large white aluminosilicate metacrysts, with highly contorted foliation planes. Possibly a metamorphosed equivalent of

GRANITE

BLACK ARGILLITE

DOLOMITE

BLACK ARGILLACEOUS LIMESTONE

DOLOMITE

BLACK ARGILLITE

HORNFELS, ARGILLITE, DOLOMITE

LIMESTONE

SCHIST, ARGILLITE, LIMESTONE

SPOTTED SCHIST

LIMESTONE, SCHIST

RENO & OLDER FORMATIONS

LAIB (UNDIFFERENTIATED)

RENO MT.

YELLOWSTONE MT.

N

SUMMIT MINE

0   1 MILE   2
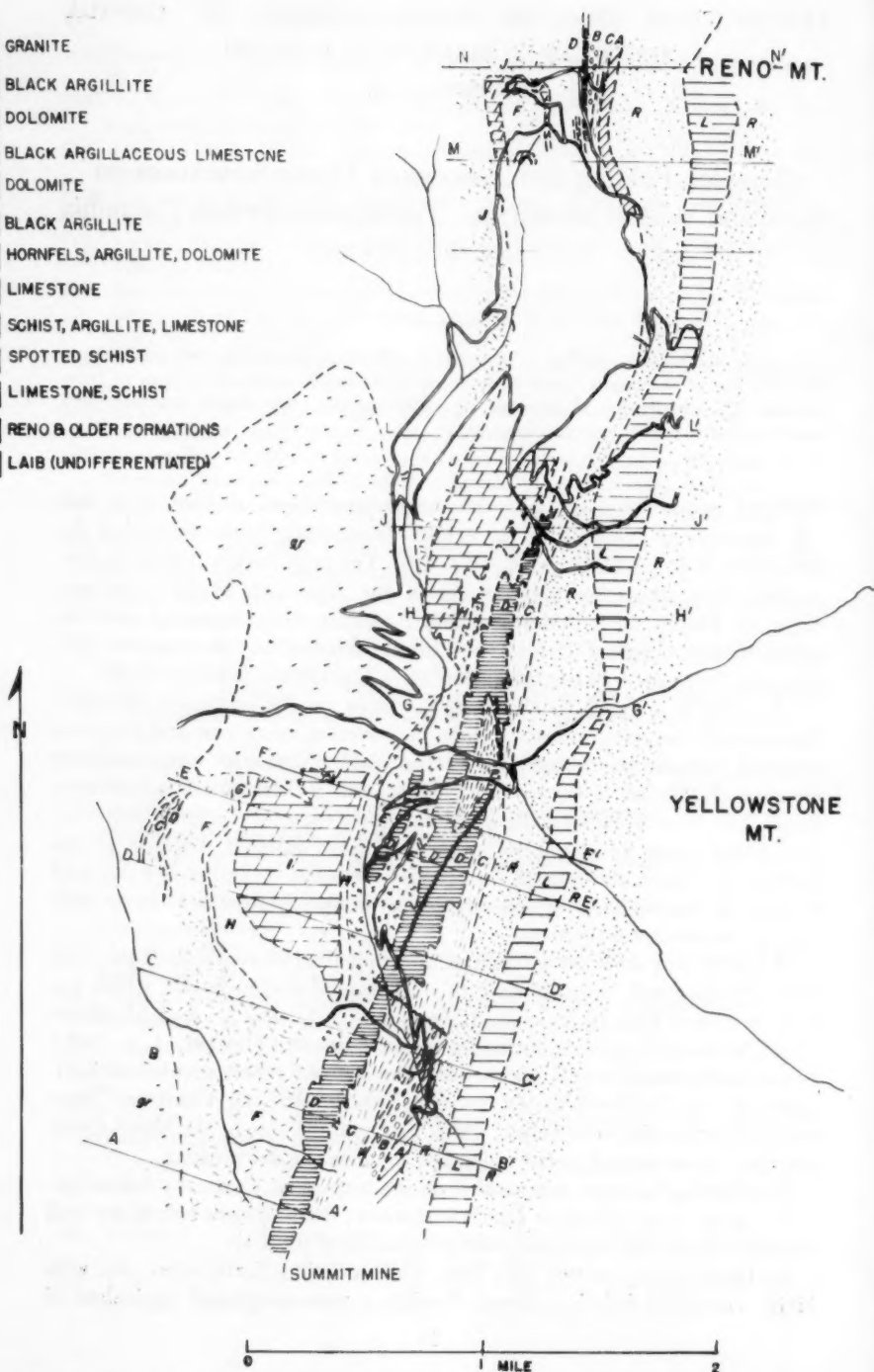
FIGURE 1. Sketch map of the Sheep Creek area, from the Summit mine to Reno Mountain.

C, this unit appears only at the south and north limits of the map area.

C: argillite, phyllite, schist, with minor calcareous and quartzitic bands. Units A, B, and C are intimately associated, and presumably belong to the Truman member of the Laib formation (1, p. 24).

D: limestone, medium to coarse grained, massive to thin bedded, often streaky and argillaceous. Strongly drag-folded and very variable in thickness. Fyles and Hewlett term it the Reeves limestone.

E: interbedded grey to black dolomite, hornfels, quartzitic beds, black to brown argillite, and limestone.

F: black, highly contorted argillite, locally siliceous. It has thin limestone beds. It possibly grades into unit E.

G: dark, massive dolomite, of variable thickness, possibly a facies of F.

H: grey to black argillaceous limestone.

I: grey dolomite, often well bedded, rich in sedimentary breccia, locally silicified, silicated, or cherty.

J: black argillite, with limestone interbeds.

Units F, I, and J are assigned by Fyles and Hewlett to the Active formation. However, a large part of the Laib formation appears to be missing, and for this reason they have postulated a fault (the Black Bluff fault) along the western boundary of the limestone of unit D. The intimate infolding between units D and E, and relationships indicated by drilling, seem incompatible with this interpretation, unless the fault occurred before at least part of the folding.

Minor Structures

Drag-folds and bedding–cleavage intersections provide many measurements of lineation in units A, B, C, D, E, and F. In units A, C, D, and E, they are generally to the north at small angles, although reversals are not uncommon, particularly south of Sheep Creek. In general, the drag-folds are consistent with the structural setting, and are dependent on the major folds in the area. Unit B at the south end of the map is an exception, since drag-folds (apparently in cleavage surfaces) plunge rather steeply to the south. Other types of lineation in this unit mostly plunge to the north. These independent drag-folds may result from bodily displacements of the schist zone, not directly controlled by folding movements.

The black argillites of units F and J are more variable in the plunge of drag-folds and linear structures than the other units. In general, the strike of minor folds and drag-folds, and the pattern of deformation, appear compatible with the structure of older units to the east. Additional evidence on this is provided in the next section of this paper. The argillites show two types of structure, evident throughout the area, but particularly well displayed above the anticlinal structure in dolomite, at the northern extremity of the map. Here cleavage and bedding are locally straight and

parallel for considerable distances along strike, while in other places they are highly contorted, intricately crenulated, and folded. In one outcrop, above a sharp flexure in the dolomite anticline, movement has been so intense as to produce rodding (in the direction of fold axes), which in cross-section closely simulates pillow-structure! From these relationships it is suggested that it may be possible to identify the position of fold axes in monotonous slaty rocks, without recognizable markers, by the prominence of crenulation, contortion, etc. The limbs of such structures are marked by strongly sheared zones of fairly persistent strike, with very pronounced, thinly laminated cleavage.

ATTITUDE OF BEDDING AND FOLIATION

Stereographic plots (on the upper hemisphere) of bedding, schistosity, and other planar structures have been made for the more important units and for the areas south and north of Sheep Creek respectively. The general pattern is illustrated by a composite diagram for the area south of Sheep Creek (Fig. 2, I). Poles to the various S-planes measured are arranged in an incomplete girdle, with a decided maximum in the southeast quadrant. The axis of this girdle corresponds well with the plotted positions of linea-tions, most of which lie in the southwest quadrant. As pointed out by Weiss (4, pp. 18–20), this pattern is the type that one would expect from isoclinal folding. A plot of poles to S-planes for units A, B, and C shows a similar pattern, with a distinct concentration indicative of rather steep easterly dips. This reflects the influence of the overturned, steeply dipping west limb of the Sheep Creek anticline. Figure 2, III, represents the similar distribution of poles in unit D. On the other hand, a very different pattern is shown by Figure 2, IV, for unit I. The generally gentle northerly dip of this element is not very different from the plunge of lineation and drag-folds in the other formations. Figure 3, V, summarizes the attitudes of S-planes in unit F, and again varies from the preceding. There is the same concen-tration of points in the southeast quadrant as is given by A, B, and C (Fig. 2, II) and by D (Fig 2, III), but the dips are noticeably flatter, because of the influence of the overlying unit I. The fold pattern is the same as for the units to the east, flattened against the nearly horizontal, massive dolomite above.

North of Sheep Creek, the composite stereographic plot (Fig. 3, VI) presents substantially the same picture as for the area to the south. Unit I (Fig. 3, VII), however, now conforms with the pattern of the other units, owing to intrusion by granite along a north–south contact or to thinning of the dolomite mass to the north.

Two conclusions are drawn from these diagrams. First, as noted earlier, the patterns indicate that the folding is essentially isoclinal, except for the massive dolomite body. Second, the pattern is so consistent throughout the various units that no major structural discontinuity (such as the Black
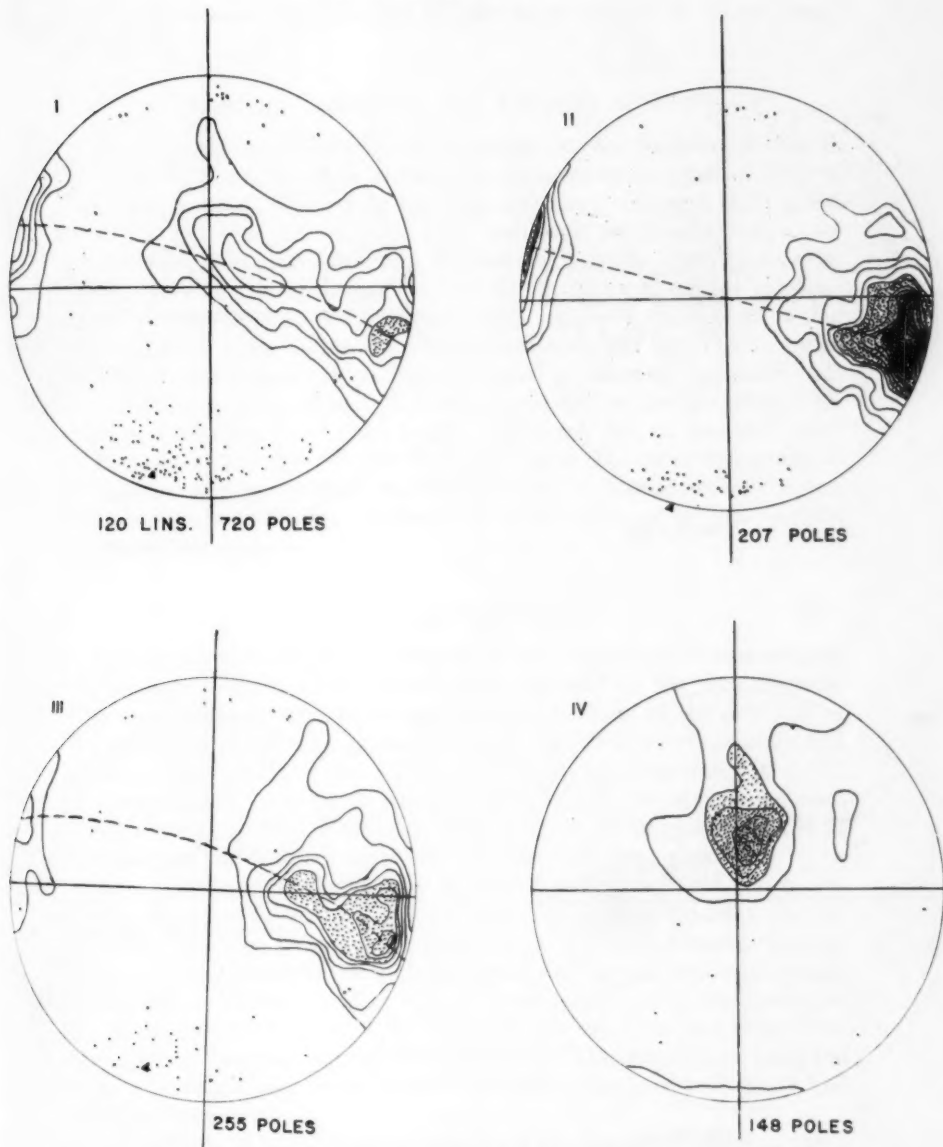
FIGURE 2. Frequency diagrams of stereographic plots (on the upper hemisphere) of S-planes. Unstippled areas, less than 5 per cent of poles per 1 per cent area; lightly stippled area, 5 to 10 per cent; moderately stippled, 10 to 15 per cent; heavily stippled area, over 15 per cent poles per 1 per cent area. Strike and plunge of lineation and drag-fold axes indicated by points; black triangle, axis of girdle which best fits contour diagrams. I: composite of all poles to S-planes south of Sheep Creek. II: plot of poles for units A, B, C. III: plot of poles for unit D. IV: plot of poles for unit I. North at top of diagram.
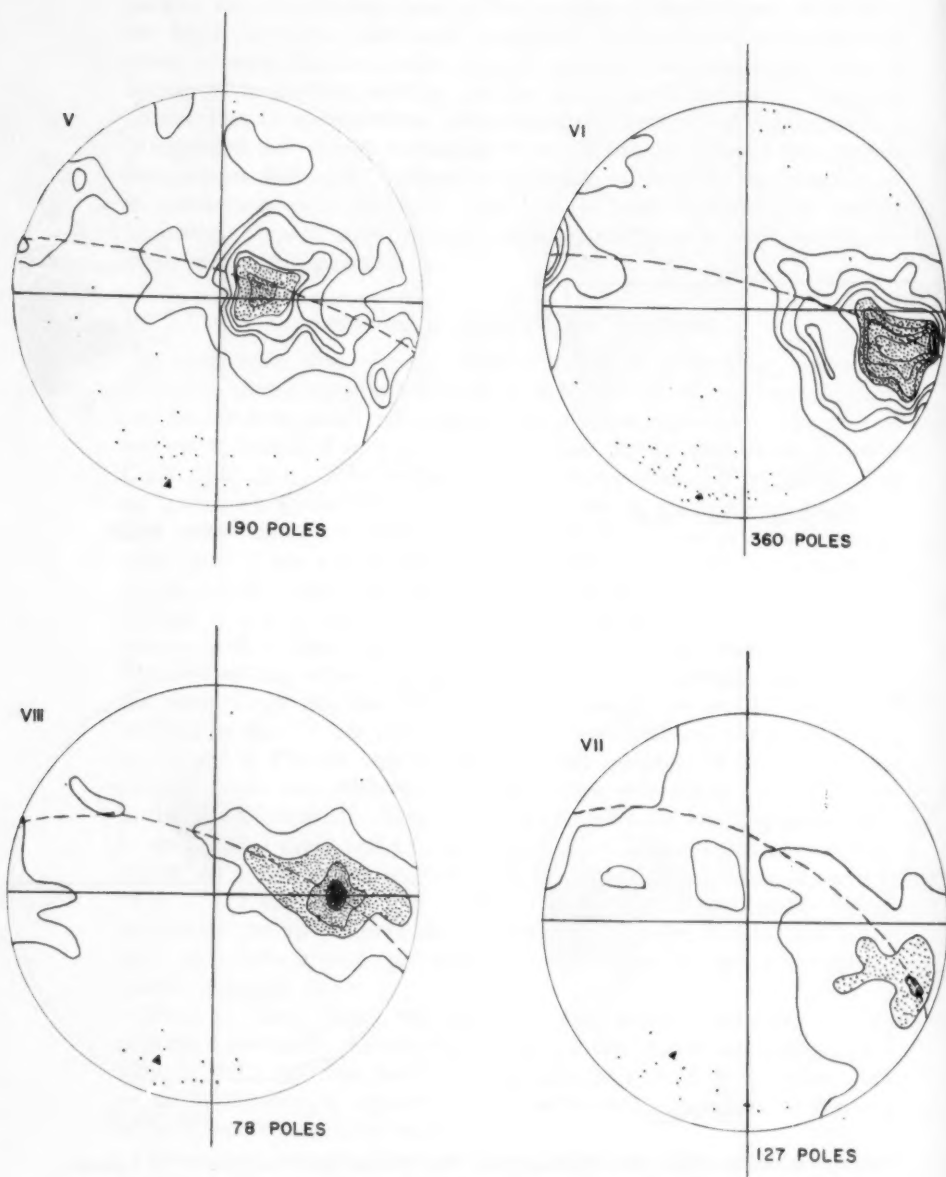
FIGURE 3. As in Figure 2. V: plot of poles for unit F, south of Sheep Creek. VI: composite of all S-planes measured north of Sheep Creek. VII: unit I, north of Sheep Creek. VIII: units F and J, north of Sheep Creek.

Bluff fault believed by Fyles and Hewlett to bound unit D on the west)
seems likely.

TECTONIC THICKENING AND THINNING OF UNITS

There appear to be considerable variations in the thickness of unit D
and units A, B, and C. West of the Reno mine, at an elevation of 6500 to
7000 feet, a band of limestone has been correlated with unit D; it is less
than 100 feet wide. Immediately north and south of Sheep Creek, at an
elevation of 3000 to 3500 feet, a thickness of perhaps 1000 feet can be
found. Some of this thickening may be due to faulting, but the relation-
ships are suggestive. Also, limestone seems relatively prominent in the
intermediate syncline within the Sheep Creek anticlinal belt. On the other
hand, unit B is known only at high elevations at the north and south ends
of the belt mapped, and only C is well represented at low elevations. This
suggests that there have been bodily migrations, due to complex drag-
folding, shear, and flow, of the lithological units. The schist zones tend to
thicken and migrate upwards, the limestones to concentrate in the synclines.
This conception has been embodied in the construction of the cross-sections
which are here presented.

THE CROSS-SECTIONS

Figures 4 and 5 represent a selection of some twenty-seven cross-sections
constructed to represent the relationships assumed in the area mapped.
The main controls were the surface geology, the form of the west side of
the Sheep Creek anticline as deduced from Matthews' excellent plans and
sections, and two drill-holes drilled in 1953 by the American Metal Co.
In preparing the sections, the forms of units D and I have been the prin-
cipal concern. No consideration has been given to the supposed Black Bluff
fault in the construction of the sections, for reasons already given.

The dominant structure in unit D is the complex drag-fold which out-
crops on the north bank of Sheep Creek. This is modified by a fault in
the Reno quartzite, known as the Queen fault. The fault dips east, and the
vertical component is that of a normal fault, with the hanging wall moving
down. This is hardly consistent with the moderate to strong overturning of
the formations to the west. It is suggested that this fault may result from
the localized dragging and thickening of unit D. The drag-fold is considered
to have persisted as a major feature throughout the area, both north and
south of Sheep Creek.

The attitude of the formations underlying the massive dolomite of unit I
can only be guessed at. The argillites to the south and west of the dolomite
are deformed in the same manner, and to at least as high a degree, as units
A, B, C, D, and E to the east. Drilling just to the south of the main dolomite
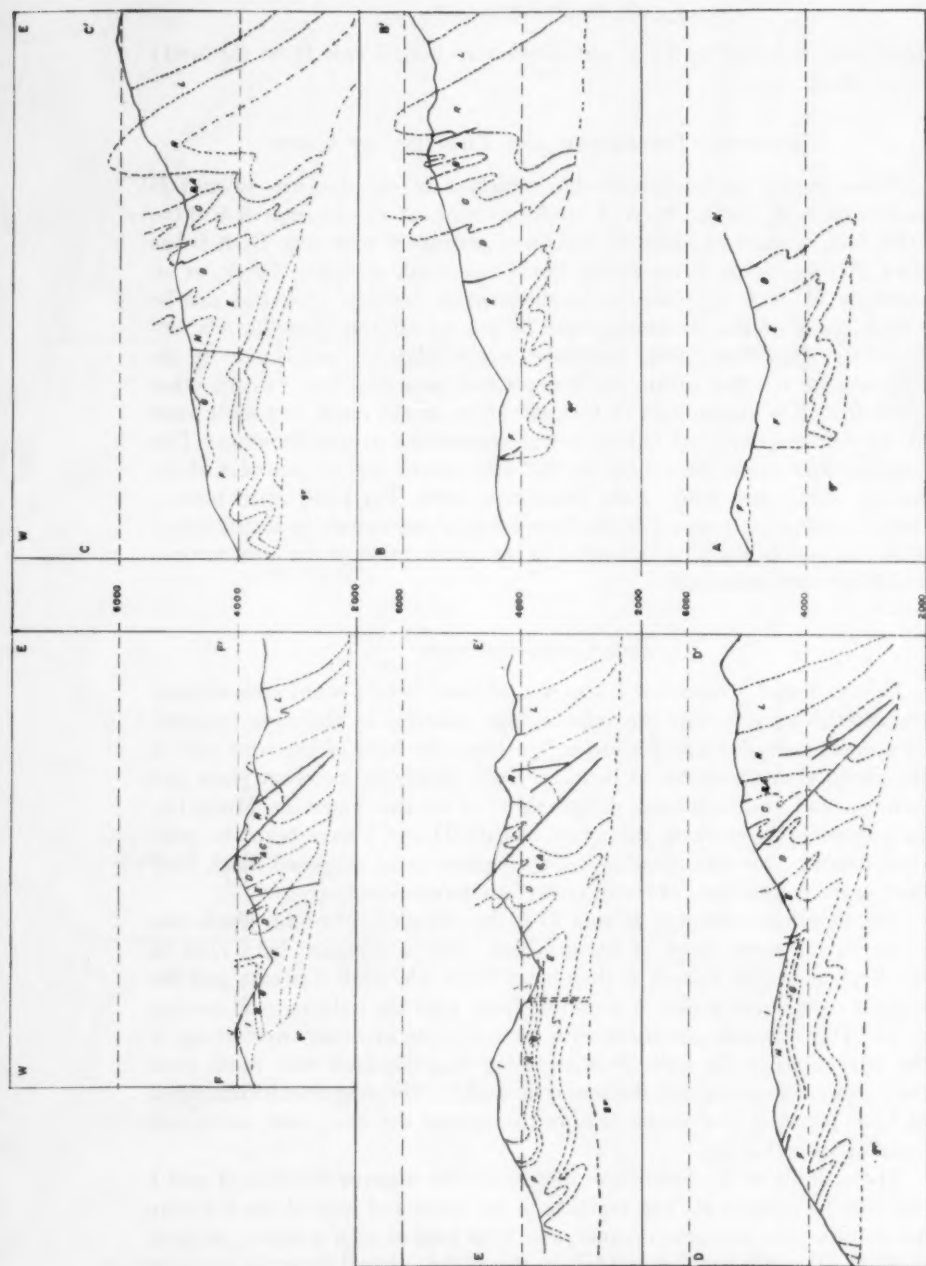indicates dips steeper than are found in the dolomite itself.

FIGURE 4. Cross-sections illustrating assumed structure south of Sheep Creek. Location of sections illustrated in Figure 1.

FIGURE 4. Cross-sections illustrating assumed structure south of Sheep Creek. Location of sections illustrated in Figure 1.
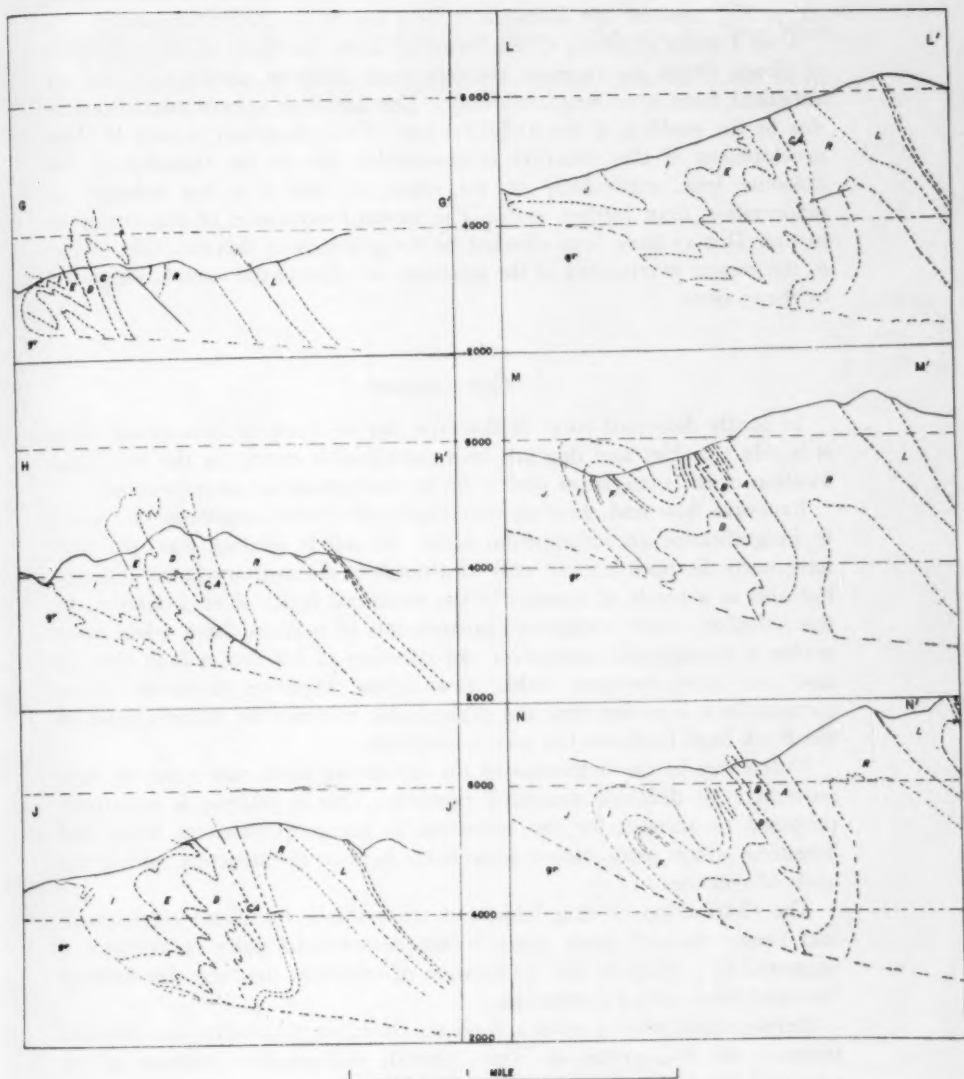
FIGURE 5. Cross-sections north of Sheep Creek.

Unit D is shown as continuing beneath the dolomite, and reappearing in a small anticline (the Udiville anticline) west of units I and F. It is a relatively thin layer of limestone, overlain by black argillite and underlain by brown to purple schist and hornfels like that of unit C. Fyles and Hewlett (1, p. 35) consider this limestone to be a unit of the Active formation.

Unit I south of Sheep Creek forms an inert, flat-lying block, and north of Sheep Creek its structure becomes more complex, developing into an anticlinal form near Reno mountain. This anticline is here interpreted as due to the swelling of the anticlinal part of the drag-fold in unit D. The development of this structure is presumably due to the thinning of the dolomite lens, particularly on the edges, so that it is less resistant to deformation than further south. The upward expansion of the drag-fold in unit D may have been effected by the pinching of this structure owing to the greater overturning of the quartzite anticline to the west, as suggested by the sections.

CONCLUSIONS

In highly deformed rocks of this type, the thickness of formational units is highly variable, and depends to a considerable extent on the structural location of the material as well as on its competence or incompetence.

Excessive flow and shearing may locally eliminate completely or reduce to insignificance an incompetent layer. To put it another way, we may have units disappearing not only as a result of sedimentary facies changes, but also as a result of changes in the structural facies or environment. In this situation, where extensive displacements of material have taken place *within* a stratigraphic succession, the question of whether a fault does or does not occur becomes rather meaningless. However, from the above paragraphs it is evident that the stratigraphic evidence for the projection of the Black Bluff fault into this area is unreliable.

Differences in the behaviour of the deforming units may result in their movement to different structural positions. This hypothesis is tentatively proposed to account for the variations in the proportions of schist and limestone which predominate respectively high in the structure and in the keels of synclines.

The distribution of drag-folds and other minor folds and crenulations and evenly sheared, platy zones within monotonous slates or argillites is suggested as a criterion for the location of otherwise unobservable folds of intermediate or major dimensions.

Stereographic plots of poles to S-planes (bedding, schistosity, and cleavage planes), the π-diagrams of Weiss, provide independent evidence of the type of folding, where outcrop is poor, and also give valuable information regarding the homogeneity of the deformation throughout a complex area.

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Manipulation Errors in Geochemistry: A Preliminary Study

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ABSTRACT

Interpretative comparisons of rock composition require knowledge of the range of variation of each type as well as its mean value. The variate is composition (x_i) or some related function (e.g., $\log x_i$) and its range is measured by the sample variance estimate s^2. This estimate is, however, biased because it includes components which arise from sampling ($s_s{}^2$), crushing and quartering ($s_c{}^2$), and analytical ($s_a{}^2$) errors. The true or geochemical variance is $s_g{}^2$, where

$$s_g{}^2 = s^2 - s_s{}^2 + s_c{}^2 + s_a{}^2.$$

Theory and applications are discussed, indicating empirical corrections which may be used.

ATTEMPTS to make quantitative interpretations in geology are always subject to two main sources of error. On the one hand, geological information is, of necessity, fragmentary and incomplete. As a result a unit (bed, fauna, stock, basin) cannot be examined in its entirety, but must be *sampled*. Since geological units are heterogeneous, no sampling scheme can give all possible information about the unit. On the other hand, we can never measure the attribute of interest in the sample itself in an unequivocal way. That is, there is an *analytical error,* and the best estimation that we can make will not give the same result twice.

It frequently happens that we wish to compare measurements on two or more different units and to decide whether or not the results differ significantly. For example, the average chromium content of the Apsley paragneiss (Peterborough County, Ontario) has been estimated as 5 p.p.m. (8), whereas the average value for a series of Shield-derived greywackes (the Charny formation (10)) is 88 p.p.m. Are these figures consistent with the hypothesis that the Apsley paragneiss was once a greywacke?

Before an intelligent answer to such a question can be made we need to know the range of variability or, in other words, the degree of confidence to attach to the average values given. There are three main sources of variation in the data: (*a*) the heterogeneity of the geological unit, (*b*) errors of sampling, and (*c*) errors of analysis. Items (*b*) and (*c*) can be controlled to some degree by the exercise of the geologist's good judgment in the field and by the experience of a careful analyst. But errors cannot be completely eradicated and, when the units are very heterogeneous

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or when the averages lie close together, it is advisable to try and assess the effect of the various manipulations which intervene between the outcrop and the interpretation.

For this it is necessary to consider both theoretical and experimental aspects. The latter can only be achieved by extended replicate analysis; this is both expensive and tedious, which explains the relative absence of this kind of study in the past. The analytical facilities of the Centre de Récherches Pétrographiques et Géochimiques at l'Ecole Nationale Supérieure de Géologie Appliquée, Nancy, where I spent the year 1959–60 on leave-of-absence, were, however, eminently suitable for such work. I was fortunate in having the kind assistance of M. le Professeur M. Roubault, Directeur de l'E.N.S.G., M. H. de la Roche, Sous-Directeur, C.R.P.G., and M. le Professeur R. Coppens, to whom I am indebted for permission for preliminary publication of material to be more fully discussed elsewhere. Dr. G. V. Middleton of McMaster University, Department of Geology, kindly read and criticized the manuscript. Most of the calculations were carried out using the McMaster University Bendix G15D Computer.

Theory

It is assumed that the distribution of an element is being studied in a geological unit. The mean value is μ, and this is estimated by a series of analysis results x expressed in weight per cent or parts per million (p.p.m.). Each measurement is subject to an error or variation (g) resulting from the geochemical inhomogeneity of the unit, and to errors of sampling (s), crushing or sample reduction (c), and analysis (a). The sampling and sample reduction errors arise from the polymineralic nature of rocks, which allows the proportion of different minerals to change during the operation of selecting part of the material available.

Denoting error terms by ϵ, we can write

$$(1) \qquad x_{gsca} = \mu + \epsilon_g + \epsilon_s + \epsilon_c + \epsilon_a.$$

It will be assumed that these error terms are random in the sense that their expected values will be zero; systematic errors or bias will be disregarded for the present. This means that the average value $\bar{x}$, obtained after replication for each subscript, will be an unbiased estimator of μ.

Further development needs some consideration of the frequency distributions involved. The terms ϵ may be considered as continuous variables and will probably be mutually independent; x will therefore also be a continuous variable, within the limits 0–100 (wt.-per cent) or 0–1,000,000 (p.p.m.).

Disregarding these limits, it is customary to regard errors as arising from the effect of numerous, small, random, and independent perturbations. If this be so, then it is often assumed that the frequency of any value assumed by a variate ϵ is given by a normal probability function with mean zero and variance σ^2. This is summarized by the following statements:

$$\epsilon_g \text{ is } N(0, \sigma_g{}^2),$$
$$\epsilon_s \text{ is } N(0, \sigma_s{}^2),$$
$$\epsilon_c \text{ is } N(0, \sigma_c{}^2),$$
$$\epsilon_a \text{ is } N(0, \sigma_a{}^2).$$

If the variance of x is σ^2, then it follows from the properties of the normal distribution that

$$x \text{ is } N(\mu, \sigma^2),$$

where

(2) $$\sigma^2 = \sigma_g{}^2 + \sigma_s{}^2 + \sigma_c{}^2 + \sigma_a{}^2.$$

This equation can be rearranged to give the following:

(3) $$\sigma_g{}^2 = \sigma^2 - \sigma_m{}^2,$$

where $\sigma_m{}^2$ represents the total manipulation variance due to sampling and analysis. Equation (3) has been published elsewhere in a somewhat less rigorous form (7); Laffitte's treatment (4) ignores the geochemical variance.

The relationship expressed in equation (3) is interesting, implying as it does that the apparent variability or variance of a set of analyses will always be greater than the variability of the material sampled. The total variance is biased by the errors picked up between the outcrop and the analysis statement. This is important for two reasons.

First of all, it impedes us from making any clear genetic interpretation of element frequency distributions. Figure 1 shows two histograms of vanadium distribution in a set of analyses of Canadian granites. These
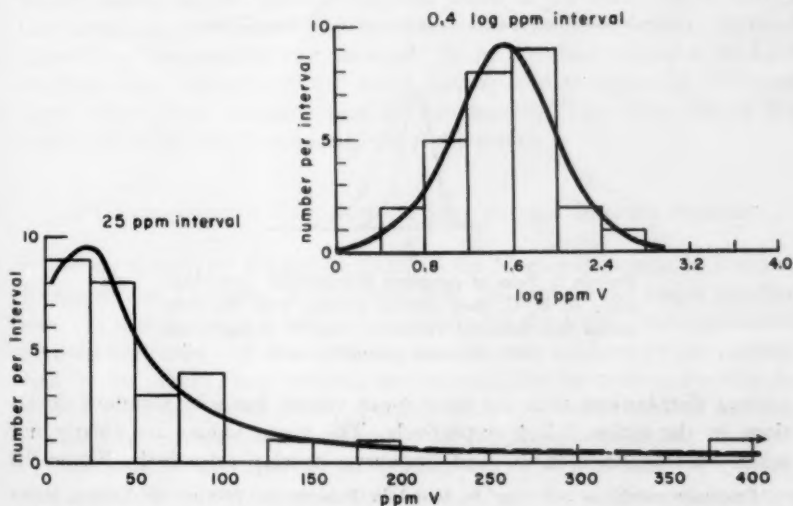
FIGURE 1. Arithmetic and logarithmic frequency distribution plots for vanadium in Canadian granite (taken from Ahrens (1), Fig. 18).

are taken from a paper in which Ahrens (1) uses such diagrams to support the hypothesis that trace element distributions follow a lognormal law. Equation (3), however, indicates that part of the spread of such histograms is in fact due to sampling and analysis errors. It is conceivable that a very homogeneous substance (e.g., obsidian, lithographic limestone) might give a wide spread of values solely as the result of a poor analysis method. This is, of course, an unlikely and extreme example,[1] but serves to illustrate the point, namely that some errors must always be present and that they will confuse the interpretation.

Secondly, it affects the results of any statistical tests which are to be used for discrimination between populations. The Student-t test and analysis of variance permit us to define the probability of a valid difference between population means in terms of the sample sizes, variances, and means. This is illustrated in Figure 2, where the first three diagrams illustrate pairs of
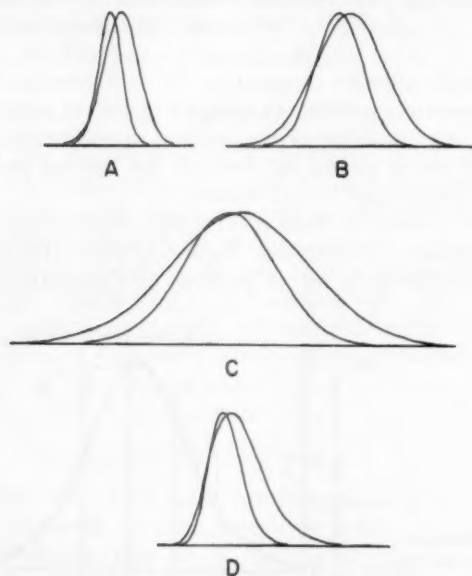
FIGURE 2. Pairs of sampling distributions (hypothetical). A, B, C show normal curves, with the same means but different variances. Pair D is lognormal with the same parameters as B.

normal distributions with the same mean values, but with standard deviations in the ratios $1:2:4$ respectively. The mean values are clearly not readily distinguished in 2C and the curves overlap extensively. Figure 2B

[1]Examples nearly as bad may be found in Bulletin no. 980 of the United States Geological Survey for the series of world-wide analyses of the standard samples G-1 and W-1.

illustrates a case where the Student-t test indicates more than 99 per cent probability that the means are different (this considers the curves as representing two samples of 100 values; the parameters are those listed for titania in Table II).

Figure 2D illustrates the additional point that non-normal skewed distributions also impede discrimination between means.

Equation (3) cannot be used in its present form. The values of σ^2, σ_s^2, etc., are estimated in practice by the measured variances s^2, s_s^2, etc. If we admit that s^2 meets the necessary conditions for a good estimator (unbiased, consistent, efficient) and denote an expected value by E, then

$$E(s^2) = \sigma^2$$

and we can transpose equation (3) to the following:

(4) $$s_g^2 = s^2 - s_m^2,$$

where

$$s_m^2 = s_s^2 + s_c^2 + s_a^2.$$

Equation (4) gives an estimator of the geochemical variance of a unit, to be obtained from the following operations. Samples of outcrops are taken from various parts of the unit; each sample is crushed and split into a number of subsamples in the form of rock-powders ready for analysis; each powder is analysed several times. If each operation is in triplicate there will be 81 analyses; quadruplicate sampling needs 256 analyses. It is clear that a large amount of labour and expense is involved. The geologist usually wants to collect from numerous points in the units, but to restrict each sample to a minimum of subsampling and analysis replication. In most cases it is "one sample, one analysis." It is, therefore, desirable to have available some estimates of σ_m^2 which can be used as correction factors in cases where direct measurements are not feasible. The remainder of this article will be devoted to some aspects of this matter.

A Comparison of Two Sample Sets from a Granite Massif

During a study of the radioactivity of the Mortagne granite in Brittany, Roubault and Coppens (5) analysed over 200 samples for major constituents (as well as for uranium). Fortunately for the writer, two methods of analysis were used and about half the samples were analysed by one method, half by the other. These two sets are very suitable for treating some of the problems of the present study, because each method yielded an estimate $\bar{x}_i$ and s_i^2 of the mean μ and variance σ^2 of the parent population.

The samples averaged about 1 kilogram in weight and were mostly diamond-drill core sections of fresh rock. One set came mostly from systematic surface collecting on a grid pattern, whereas the other comprised subsurface samples from deep drilling and mine workings.

The first analytical method was an adaptation of the so-called rapid methods of silicate rock analysis developed at the E.N.S.G., Nancy (2). The second method used the spectrograph (quantometer) except for the alkalies (flame photometer) and ignition loss (gravimetric) and was similarly developed at the E.N.S.G. (6). Both methods have been used continually in Nancy for the last few years and complement each other well, because each has certain advantages which the other does not.

The granite is white to pink, leucocratic, and massive. The grain size is medium–coarse with subhedral microcline microperthite grains up to 10 mm. long in a somewhat finer-grained matrix. The average mode (based on point-counting thin sections of two typical specimens) is given in Table I along with the over-all average chemical composition from all

TABLE I

Composition of the Mortagne Granite

	Vol.-per cent		Wt.-per cent	
			$\bar{x}$	Range
Potash feldspar	45.0	SiO$_2$	71.93	67.20 to >75
Albite-oligoclase	20.0	TiO$_2$	0.18	<0.04 0.69
Quartz	21.0	Al$_2$O$_3$	15.34	11.56 20.6
Muscovite	9.0	Fe$_2$O$_3$*	1.98	0.70 6.45
Biotite	5.0	MnO	0.02	Tr. 0.19
Apatite, etc.	Tr.	MgO	0.62	Tr. 2.25
		CaO	0.75	<0.03 4.31
Total	100.0	Na$_2$O	2.99	0.10 4.65
		K$_2$O	4.81	2.00 7.44
		P$_2$O$_5$	0.35	Tr. 0.77
		Total	98.97	

*Total iron as Fe$_2$O$_3$.

the analyses. There is little variation evident from hand-specimen study but the range of variation is included in Table I. A total of 229 rocks were analysed, 119 by the spectrographic procedure and 110 by the chemical methods. Not every constituent could be determined in each rock, since in some cases the amount present was outside the working range. Thus, for MnO only 41 and 96 values, respectively, were available, and these were too close to the sensitivity limit to be of much value for comparison here. The data are adequate, however, for the comparison of Si, Ti, Al, Fe, Ca, Na, and K (both methods for alkalies were by flame photometer).

Table II contains the following spectrographic and chemical data for weight per cent SiO$_2$ and TiO$_2$: number of analyses, mean, variance, standard deviation, coefficient of variation in per cent. Individual analyses will be listed in a later article. Silica was chosen because it is the most abundant constituent and occurs in almost all of the minerals of the rock; by contrast, titania is a minor component which occurs mainly in one mineral only (biotite). The sampling and analysis errors could be widely different

TABLE II

WEIGHT PER CENT STATISTICS FOR SiO_2 AND TiO_2

		SiO_2	TiO_2
Spec.	n_1	119	119
	$\bar{x}_1$	72.18	0.163
	s_1^2	3.163170	0.00508427
	s_1	1.779	0.0713
	C_1	2.5 per cent	44 per cent
Chem.	n_2	110	110
	$\bar{x}_2$	71.68	0.196
	s_2^2	2.641394	0.01085501
	s_2	1.625	0.1042
	C_2	2.3 per cent	53 per cent

for two such oxides. This appears to be confirmed by the results, since the coefficients of variation show large differences.

As previously mentioned, we may be reasonably sure that the specimens are samples of a single population. The F test of Snedecor is used to test the hypothesis that s_1^2 and s_2^2 are both estimates of the same population variance σ^2. The relevant figures are given in Table III, from which it is

TABLE III

TESTS ON VARIANCE AND MEAN OF SiO_2 AND TiO_2

	SiO_2		TiO_2	d.f.
F	1.20		2.14	109,118
$F_{0.95,120,120}$		1.35		
$F_{0.995,120,120}$		1.61		
Significance	NS		***	
t	2.19		2.83	227
$t_{0.975,120}$		1.98		
$t_{0.995,120}$		2.62		
Significance	**		***	

NOTE: These are one-sided tests, i.e., NS means not significant at $P = 0.90$; * means significant at $P = 0.90$; ** means significant at $P = 0.95$; *** means significant at $P = 0.99$.

concluded that the hypothesis may be accepted for SiO_2, but is improbable for TiO_2. Of course, the variances tested have not yet been corrected using equation (4).

Similarly we may use Student's t-distribution to test the hypothesis that the means $\bar{x}_1$ and $\bar{x}_2$ both estimate the population parameter μ. In the case of titania, the usual test has been modified to take account of the significant difference in variances. The results of the test are also given in Table III, where it is seen that the means are probably significantly different in each instance, but especially for TiO_2. This might arise from one of several reasons: (a) the population means are equal and the test has given the wrong result; (b) the means are equal and the population

is not normal; (c) the means are equal and the sampling was not random; (d) the means are different because of analytical bias, but the geochemical population means are identical; (e) the means are different because the unit under study is heterogeneous in some way (this is perhaps the "obvious" reason).

Among these several possibilities we will reject (a), for if the probability of error for silica is less than 5 per cent and that for titania is less than 1 per cent, then the joint probability is less than 0.05 per cent. There is no geological evidence supporting (e), which will also be rejected. The sampling was clearly non-random, but was systematic. However, a set of systematically spaced samples may in certain circumstances be taken as a single random sample and it can be argued that we are here comparing two random samples. Item (c) cannot be rejected, but for the present it seems less important than the remaining two possibilities. Departures from normality are likely to be serious when C is greater than about 20 per cent (7). This is the case for TiO_2 but not for SiO_2 and we must examine the situation further. In the case of silica, however, it seems most likely that we are here concerned with a systematic error or bias in one or both of the analytical methods.

Information bearing on this point can be adduced for the quantometric method. Two series of analyses, comprising 32 and 31 replicates respectively, were made of the standard granite G-1 (6). The average values for SiO_2 were 73.00 and 72.70 wt.–per cent, whereas the recommended value (3) is 72.86. These three values agree well, but more recent evaluation of G-1 (9) indicates that Fairbairn's estimate was too high. The true value is likely to be between 72.5 and 72.7, suggesting that the quantometric grand mean of 72.85 is a little high. In chemical methods, however, there is a "tendency for routine determinations of silica to be low" (9, p. 55), so the difference of 0.50 per cent between the mean values on the Mortagne granite may well be a systematic error with components from each method. It is of interest that the 97.5 per cent confidence interval for the spectrographic mean minus chemical mean lies between −0.012 and +1.012 per cent.

MANIPULATION ERRORS FOR THE MORTAGNE GRANITE

In the previous section we saw that the two variance estimates for silica were compatible with the hypothesis of a single population, but this was not the case for titania. Corrections will now be made as indicated by equation (4).

Analysis errors were estimated for each method by repeatedly analysing standards over a period of months. The standard deviations and variances given in Table IV were selected from the figures available in the E.N.S.G. laboratories as being the most appropriate to use for a granite. The value of s_a for the chemical determination of TiO_2 ($C = 19.1$ per cent) was

TABLE IV

ANALYSIS AND SAMPLING VARIANCE ESTIMATES
FOR SiO_2 AND TiO_2

		SiO_2	$TiO_2 \times 10^4$
Spec.	s_a	1.37	77.0
	s_a^2	1.8769	0.5929
Chem.	s_a	1.08	342.0
	s_a^2	1.1664	11.6964
	s_s^2	0.024950	0.0565

the highest value available. It was selected because the titania content is near the sensitivity limit, and the precision of chemical methods is low in these circumstances.

Since direct measurement of the sampling variance s_s^2 was not possible, it was calculated for each element by the method of Laffitte (4), which uses the following information: weight of the sample, average grain size, modal composition, concentration of the element in the rock and in each mineral. Certain assumptions are necessary, the chief one being that of equal grain size for all minerals.

The same kind of calculation may also be made for the crushing and quartering procedure, yielding an estimate of the variance s_c^2 for each element. In the present case the calculated variances are so much smaller than the sampling and analysis terms that they may be ignored.

The calculated sampling variances are included in Table IV, and are seen to be considerably smaller than the analysis errors. If this result is reliable, it vindicates the field sampling procedure, and indicates that one-kilogram samples may be suitable for sampling a medium to coarse granite.

The correction of the total variance in accordance with equation (4) is given in Table V. The residual or geochemical variance should be a measure of the degree of heterogeneity of the unit sampled, free from manipulation errors; that is, the two entries for each element both estimate population variance for that element, and the expected value of their ratio

TABLE V

VARIANCE COMPONENTS FOR SiO_2 AND TiO_2

	Source	SiO_2			TiO_2		
		Spec.	Chem.	F	Spec. $\times 10^4$	Chem. $\times 10^4$	F
s^2	Total	3.163170	2.641394	1.20	50.8427	108.5501	2.14
s_s^2	Sampling	0.024950			0.0565		
s_a^2	Analysis	1.8769	1.1664		0.5929	11.6964	
s_m^2	Manipulation	1.901850	1.191350		0.6494	11.7529	
s_g^2	Residual	1.261320	1.450044	1.15	50.1933	96.7972	1.93
	Significance			NS			***

F is unity. The actual ratios are given and it is seen that although F for TiO_2 remains highly significant, both values are less significant than in the uncorrected case. That is, the corrections are in the right direction but not in the right proportion.

The results for TiO_2 clearly need further examination. First of all, we should see what confidence we have in the estimates of the residual variance. In other words: (*a*) what is the probability that the true residual variance is zero and that all the measured variance is caused by manipulation errors, and (*b*) what is the probability that the measured variance is all geochemical, and that manipulation errors are nil?

The second alternative is quite improbable in the light of common sense and also from the earlier discussion of the significance of the F-ratios between total variances for different methods. For the first case, however, the total measured variance s^2 is greater than the assumed manipulation variance s_m^2. To test whether this is reasonable we assume that the manipulation variance is a constant σ_m^2 for each population. Then the random sampling distribution of $(n-1)s^2/\sigma_m^2$ will be a χ^2 distribution with $(n-1)$ degrees of freedom, provided that we have a normal population. In Table VI are

TABLE VI

ONE-SIDED CHI-SQUARED TESTS FOR SiO_2 AND TiO_2

	SiO_2		TiO_2	
	Spec.	Chem.	Spec.	Chem.
d.f.	118	109	118	109
χ^2	196	242	9200	1000
Significance	***	***	***	***

$\chi^2_{0.99,120} = 158.95$ for $P = 0.98$.
$\chi^2_{0.995,120} = 163.64$ for $P = 0.99$.

shown the calculated values of χ^2 together with values of the function χ^2_{120} for 99.0 and 99.5 per cent probability. It is seen that the values of total variance are all significantly greater than the manipulation variances at the 99 per cent probability level. It is concluded that the geochemical variance estimates are significantly greater than zero.

The F-test for geochemical variance of TiO_2 is 1.93 (Table V) and indicates a significant difference between the two populations. It remains to consider whether this arises from a deviation from normality.

Provided that a sample population is large enough it can be tested for deviations from normality by several methods. Among the most useful are calculations of the third and fourth moments, but the simplest is the graphical plot of the cumulative frequencies in equal class-intervals using normal probability paper: a normal distribution gives a straight-line graph. This test is qualitative as usually performed, but serves to indicate whether more laborious methods are worth while.
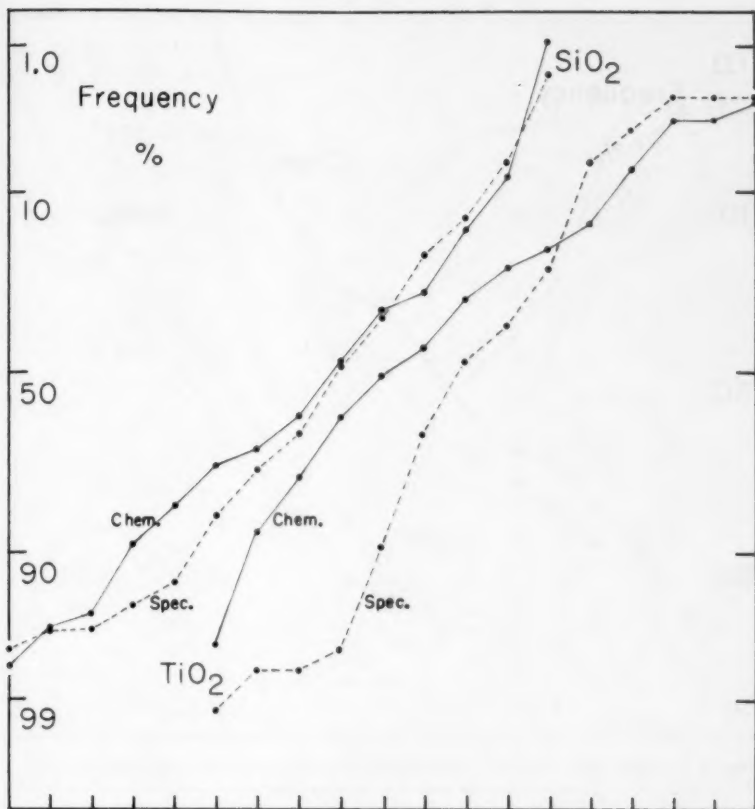
FIGURE 3. Cumulative frequency distributions of SiO_2 and TiO_2 in the Mortagne granite, on normal probability paper.

The plots for silica and titania are shown in Figure 3. Fifteen classes were used in each case and the class intervals were 0.6 and 0.5 per cent SiO_2 and 0.02 and 0.03 per cent TiO_2, for the spectrographic and chemical methods respectively. It is evident that the silica populations are fairly close to normality. Titania, by contrast, shows marked deviations, as was to be expected in view of the large coefficients of variation discussed earlier. It is notable, moreover, that the two titania distributions differ between themselves.

In view of the large coefficients of variation for TiO_2 in Table II, it might be expected that a logarithmic transformation of the data would yield a distribution showing a closer approximation to normality. Accordingly, the data x_i (for silica also) were transformed to $\log_e x_i$ values and regrouped in fifteen equal class-frequencies. The cumulative plots are shown
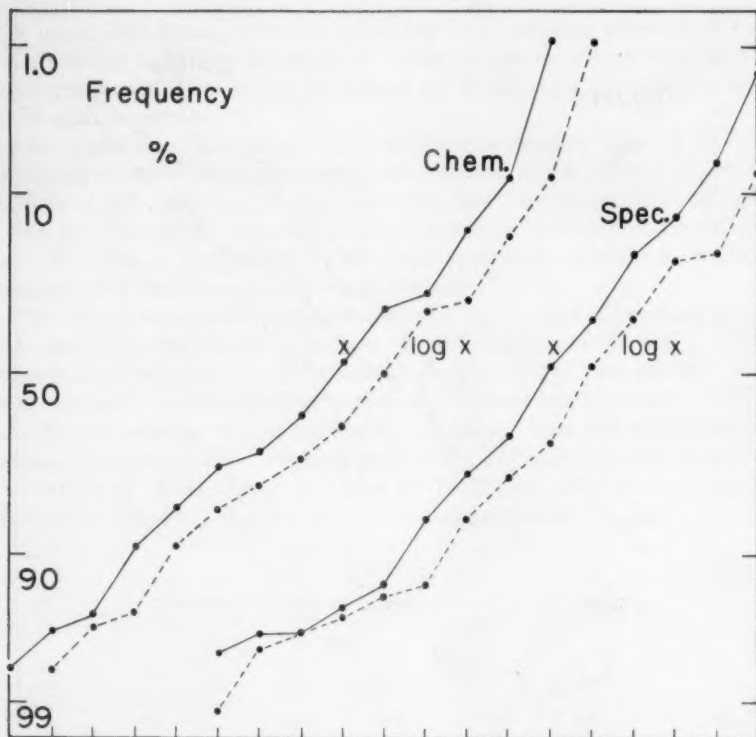
FIGURE 4. Cumulative frequency distributions for SiO_2 in the Mortagne granite (wt.-per cent and log wt.-per cent).

in Figures 4 and 5, with the arithmetic plots for comparison. There is clearly no advantage gained in the case of SiO_2, and for TiO_2 the transformed data show even less tendency to normality than before. This conclusion may be contrasted with the visual impression gained from Figure 6, which is a histogram of the chemical data on TiO_2. This histogram, with a marked positive bias (median less than mean), "looks like" a lognormal distribution. The cumulative plot suggests that this view is erroneous and, in fact, a χ^2 test for the agreement between observed and calculated frequencies confirms somewhat better agreement with an arithmetic normal distribution (probability 20–50 per cent as against 10–20 per cent).

Nevertheless it is clear that neither of the distributions of TiO_2 is close to being normal. The highly significant F-ratio for the residual variances in Table V may, therefore, not imply that we must abandon the original hypothesis that the two sets of data are large samples from one population. One or both of the following explanations is to be preferred: (a) the data
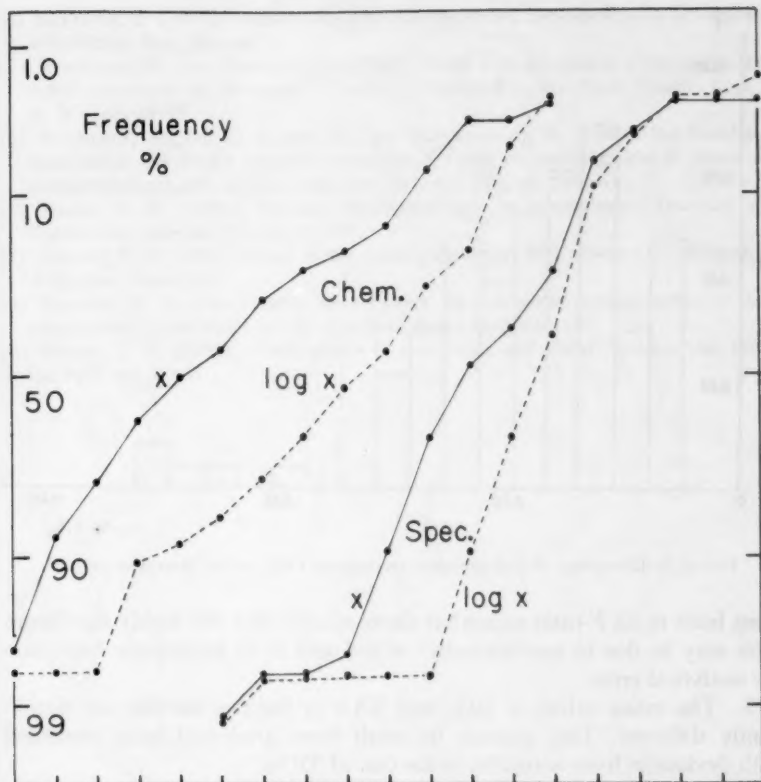
Figure 5. Cumulative frequency distributions for TiO_2 in the Mortagne granite (wt.-per cent and log wt.-per cent).

are not amenable to variance analysis, which depends on normality assumptions; (b) the assumed analytical errors are much too small.

Conclusions

1. A theory has been outlined for the empirical correction of the observed variance of a geological unit for the effects of sampling and analysis errors.

2. The theory has been tested on two large samples taken from a single population (the Mortagne granite) and analysed by different methods.

3. In the case of the most abundant constituent, silica, the corrections work in the right direction; that is, the F-ratio of the two sample variances is closer to unity when corrections have been applied.

4. In the case of a minor constituent, titania, application of the correc-

FIGURE 6. Histogram of 110 chemical analyses of TiO_2 in the Mortagne granite.

tions leads to an F-ratio somewhat closer to unity but still highly significant. This may be due to non-normality of the data or to inadequate correction for analytical error.

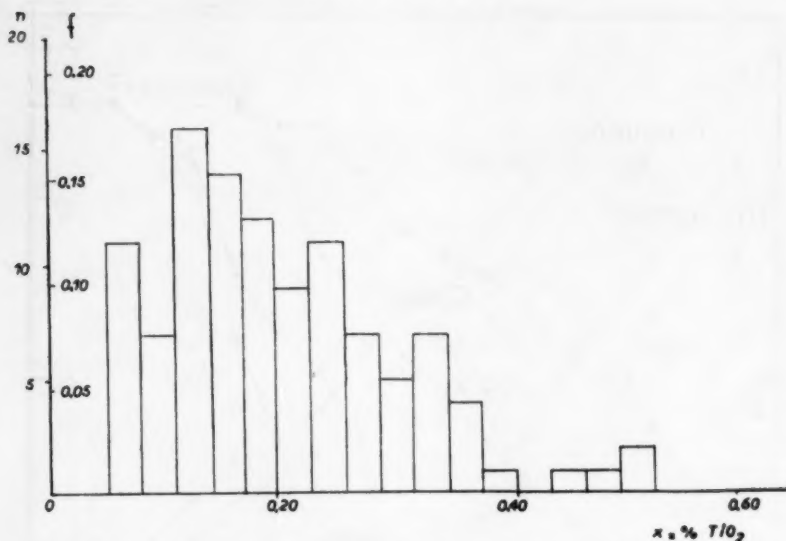5. The mean values of SiO_2 and TiO_2 in the two samples are significantly different. This appears to result from analytical bias, combined with deviations from normality in the case of TiO_2.

6. The calculated sampling errors were less important than analysis errors in the Mortagne granite study.

7. Tendencies of sample distributions to approximate to lognormality should not be judged qualitatively by inspection of histograms.

Several of these conclusions require further work (e.g., 4, 6, and 7). In particular, the empirical corrections proposed here need confirmation from a study measuring analysis sampling as well as chemical errors on the population itself. Such a study is under way and will be published elsewhere.

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Recognition of the Quartzite Breccia in the Whitewater Series, Sudbury Basin, Ontario

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ABSTRACT

Quartzite breccia has been identified in the South Range, Sudbury basin, in the Whitewater series, where it comprises the base of the Onaping formation. This siliceous rock was first called conglomerate, then pyroclastic breccia, and, most recently, rhyolite and rhyolitic breccia.

During field and laboratory studies over the past nine years, it has been seen that much of the rock was drag-folded and tectonically-transported material. Six recent chemical analyses of the quartzite breccia have shown a silica composition ranging from 86.8 per cent to 91.4 per cent SiO_2, emphasizing the sedimentary origin of the original rock.

AS part of a comprehensive study of the Sudbury Nickel Irruptive for the International Nickel Company, the writer has, over a period of nine years, made a serious study of a striking white quartzite breccia that is particularly well developed along the South Range where it forms the base of the Onaping formation, immediately overlying the Irruptive.

The breccia at the base of the Onaping formation, the lowermost formation of the Whitewater series, has been widely discussed and variously interpreted by students of Sudbury geology. Coleman (4) originally referred to it as the Trout Lake conglomerate. Subsequent workers have referred to these basal rocks as breccias and agglomerates of pyroclastic origin (2; 7; 5; 6). Some modifications were introduced by Chute (3) and Yates (14), who refer to local occurrences of the quartzites as feldspathic and arkosic. Most recently, Thomson and Williams, in government reports and papers dating from 1956 to 1959 (9–13), have concluded that the rocks of this breccia are rhyolite and rhyolite breccia comprising Pelean domes and auto-brecciated dike-feeders. To quote a recent paper (10, p. 13), "Andesitic magma rose through consolidated and brecciated rhyolite to the surface and rushed down slopes carrying rhyolitic débris to form glowing avalanche deposits."

In the South Range of the Sudbury basin, this layer of quartzite breccia (much of it 200 to 300 feet wide), at the base of the Onaping formation, extends, where not disturbed by folding and faulting, continuously from the southwest to the northeast corner of the basin (Fig. 1). The breccia consists of closely packed angular fragments of quartzite that show a considerable range in size (Fig. 2). The largest quartzite fragment seen in the breccia measured about 250 feet by 75 feet. From this size of fragment
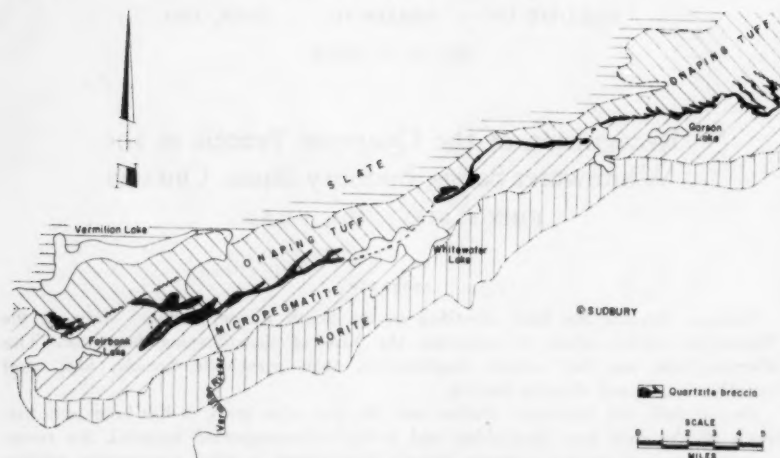
FIGURE 1. Quartzite breccia, South Range, Sudbury basin, Ontario.

FIGURE 2. Quartzite breccia.

there is a graded decrease to fragments about one inch in average dimension.

By far the most dominant rock type within the breccia is quartzite, but quartzite that has been variously altered. A few adventitious fragments of other rock types may be found within the breccia layer, but close to its

borders. These "foreign" fragments occur where there has been intense later deformation and have apparently been tectonically moved along shears into the breccia.

A rather continuous layer of coarse *volcanic* breccia with a great variety of rock types among its widely spaced fragments lies above and adjacent to the quartzite breccia, but it is distinct from and not to be confused with the quartzite breccia.

FIGURE 3. Drag-fold in quartzite.

The individual fragments of the quartzite breccia possess structural, textural, and compositional features that serve to identify the rock as quartzite. Many fragments show a well-developed tabular bedding parallel to the long sides of the breccia slab. However, in one part of the layer some of the larger fragments show an intricate pattern of domal and drag-folding resulting in folds that range in size from a few inches to four feet from crest to crest (Fig. 3). The intricately folded quartzite in these fragments is invariably thin bedded, in beds or laminations about 1 centimetre in

thickness, separated by thin sericite-rich partings. This involved, small-scale folding may be the result of soft-rock deformation or of deformation of a thinly bedded argillaceous phase of the quartzite. It is interesting to note that a sample of this intricately folded quartzite had a silica content of 89.7 per cent.

In describing the texture and composition of the quartzite, it is convenient to use the principal colours shown in outcrops by the various modifications of the quartzite. A common colour-type is a yellow-green sericitic quartzite that occurs among the fragments throughout the length of the breccia layer, but is more abundant towards the easterly end of the basin. This type is significant because it contains minor but conspicuous pebble-beds (Fig. 4), which range from ½ to 6 inches in width and contain
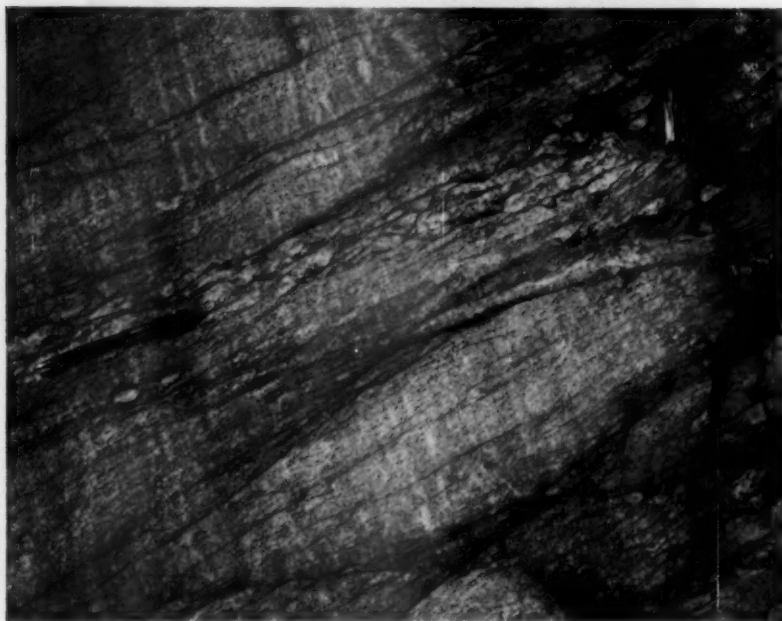
FIGURE 4. Pebble-bed in quartzite.

lenticular pebbles from ¼ to ½ inch in diameter, all set in a weaving sericitic matrix. The presence of these pebble-beds within otherwise massive and finer-grained quartzite is evidence of the sedimentary origin of such quartzite.

As seen under the microscope, this fine-grained yellow-green quartzite consists of fairly closely packed grains of quartz, ¼ to 1 mm. in size, between which weave folia of sericite. It must be noted, however, that larger-sized grains, ⅛ to ¼ inch, and pebbles up to 1 inch in diameter

occur widely scattered, but not always in beds, throughout the quartzite. A chemical analysis of this quartzite shows a silica content of 89.4 per cent.

This yellow-green quartzite is significant because it is the relatively unaltered phase from which perhaps the most common colour-type, a cream-coloured, feldspathized phase, has been developed. This feldspathization can be progressively traced through several stages of development. The first stage is yellow-green quartzite that is cut by cream-coloured albite-rich veinlets, a second stage is one in which we have a breccia (Fig. 5)

FIGURE 5. Breccia formed by albite replacing quartzite.

of yellow-green quartzite in a cream matrix, and a third stage is one in which large areas of cream quartzite show no evidence of the original yellow-green quartzite. These successive stages may all be followed within the limits of individual quartzite breccia fragments.

The end result of this alteration is the massive cream quartzite that is very abundant in the central 24-mile portion of the quartzite breccia layer. As seen under the microscope, this quartzite consists of a strikingly patchy distribution of anhedral grains of chess-board albite (Fig. 6) up to 0.5 mm. in diameter interstitially developed between grains of recrystallized quartz; i.e., here we have patches of extensively feldspathized quartzite occurring between areas that are much less feldspathized (Fig. 7). Further microscopic evidence in support of the replacement origin of the albite in this
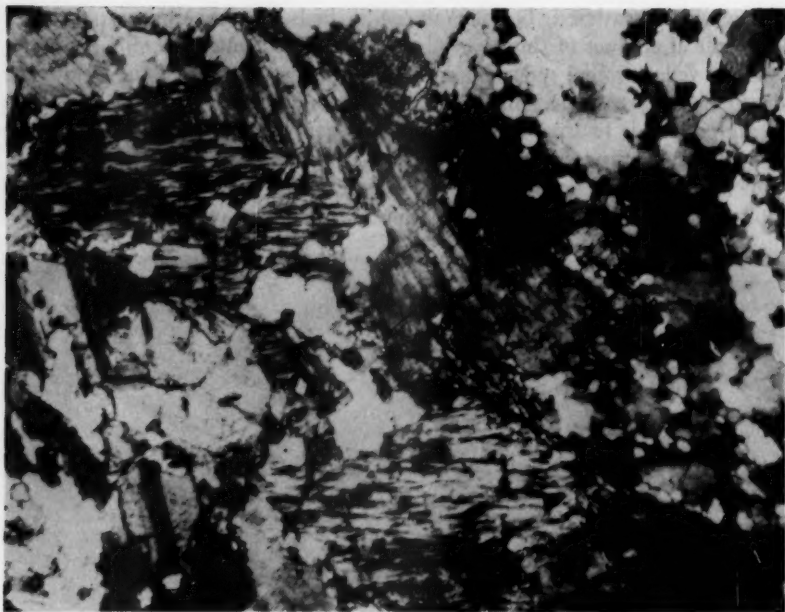
FIGURE 6. Quartzite feldspathized by chess-board albite. Width of field, 1.5 mm.
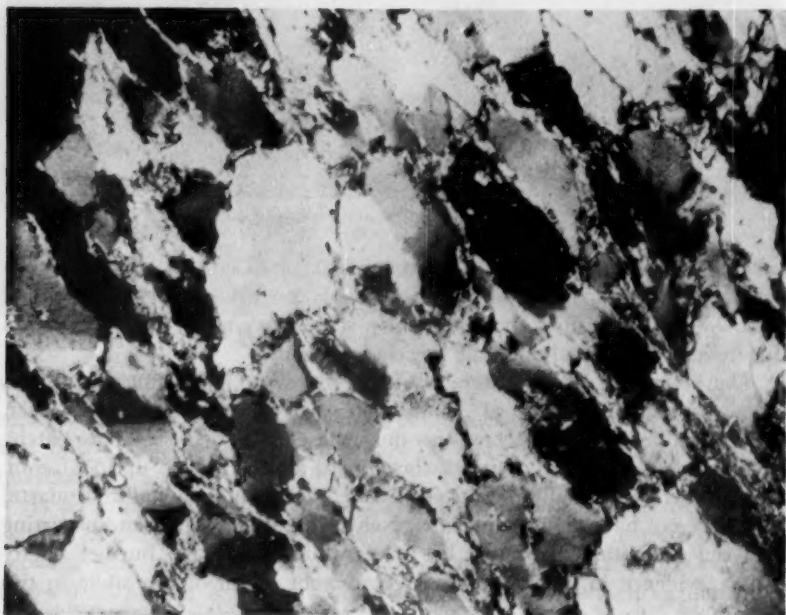

FIGURE 7. Non-feldspathized quartzite. Width of field, 1.5 mm.

cream quartzite is seen in the many occurrences of tongues and veinlets of albite between and in individual quartz grains. A chemical analysis of this quartzite shows a silica content of 87.6 per cent.

So far, I have discussed the identity of the quartzite fragments, both large and small, in the breccia layer and only referred briefly to the matrix of this breccia. This matrix is hard to define. It appears to have been originally merely more finely crushed quartzite, because one can trace the development of the breccia from the fractured borders of large blocks, through close-packed breccia fragments, into small but recognizable breccia fragments which are less closely packed. However, this matrix has been modified by replacement by the uppermost portion of the micropegmatite member of the nickel irruptive.

As seen in thin section, the "micropegmatization" consists of the replacement of the matrix by euhedral albite and by a little granophyre and biotite. The euhedral albite is related to the micropegmatite and is to be distinguished from the earlier anhedral chess-board albite. Detailed thin-section studies of many suites of specimens taken from the normal micropegmatite of the irruptive across the contact phase and into the matrix of the breccia demonstrate a progressive decrease in grain size of the micropegmatite and decrease in amounts of granophyre and biotite across the contact and into the matrix of the breccia.

Field relationships and thin-section studies indicate that the breccia matrix is an upper phase of the micropegmatite that permeated and progressively replaced the matrix of the brecciated quartzite above the main mass of the irruptive.

Six samples of the quartzite were taken for silica determinations. From what I have just said about albitization of the quartzite, and of micropegmatization of the breccia matrix, it will be appreciated that samples of this quartzite should be carefully taken with due regard to the effects of these processes in the material sampled. In the sampling an attempt was made to include as little of the breccia matrix as possible.

The silica content of the samples is given in Table I. As may be seen from the table, it ranged from 86.0 to 91.4 per cent. A search of the literature has revealed that these values are considerably in excess of the usual

TABLE I

SILICA CONTENT OF SAMPLES (ALL GARSON TOWNSHIP)

Sample number	Location	Description	Silica (SiO_2) Content (per cent)
1	Lot 12, conc. VI	Cream quartzite, with some matrix	86.0
2	Lot 12, conc. VI	Cream quartzite, matrix carefully excluded	91.4
3	Lot 12, conc. V	Drag-folded, thin-bed, cream, albitized quartzite	89.7
4	Lot 6, conc. VI	Cream, albitized quartzite	87.6
5	Lot 6, conc. VI	Green, relatively non-albitized quartzite	89.4
6	Lot 6, conc. VI	Albitized pebble-bed in sample 4	86.8

70 to 71 per cent characteristic of rhyolites and that they more nearly represent the silica content of quartzites, variously modified by the alterations described above. These high silica analyses serve to emphasize the sedimentary origin of the original rock.

The external structure of the breccia layer is significant because of its control of the distribution of the areas of quartzite breccia. The layer is fairly uniform in thickness (200 to 300 feet) along the central portion of its length, but towards either end of the basin drag-folding has considerably thickened and thinned the apparent width. The drag-folds have, in general, closely oppressed limbs that trend northeasterly at the west end and easterly at the east end of the basin and are steeply overturned northward so that they now dip steeply southward in accordance with the southward dipping foliation and overthrust structures that characterize the South Range. In many places, these drag-folds result in limbs of quartzite breccia that extend considerable distances into the overlying tuffs.

The numerous isolated blocks of quartzite and of quartzite breccia that occur some distance, up to a mile, into the tuffs, are closely related in distribution to the arms of the drag-folds and dislocation or tectonic transport. Detailed mapping shows that the isolated blocks occur almost exclusively at the ends of the basin and along the projected extensions of the limbs of the drag-folds found there. They are displaced blocks of quartzite that have been separated from the limbs of the folds by tectonic transport during the intense overthrusting that followed the drag-folding.

The pyroclastic deposits that overlie the layer of quartzite breccia, and which, along with the latter, comprise the Onaping tuff formation, have features that indicate that they are the result of normal air-borne fall-out, intermingled in places with water-borne sedimentary material. The dimensions of the fragments range from about 5 feet to about 1/32 inch. The larger sizes include blocks of quartzite, coarse porphyritic granite, and light green lavas, but the finer material consists of shard-like fragments of lava, and grains of quartz.

Classification of these fragments in mapping, by size-distribution groups, makes it possible to map certain size-distribution zones that range from 100 to 1,000 feet in width and extend for considerable distances along the strike. When such zones are mapped, the tuffs are found to possess a definite layering parallel with respect to the individual zones. Furthermore, where not disturbed by drag-folding and later disruption, this layering is also parallel to the quartzite layer and to the upper contact of the nickel irruptive. In another connection, a somewhat similar observation has been made by Zurbrigg (15, p. 343): "At surface the layering in the nickel intrusive parallels the layering in the volcanics and sediments, so it is assumed, without contradiction from diamond drilling or mining, that the nickel intrusive is also basin-shaped."

Despite the abundance of lava shards and lack of fine-scale bedding, the pyroclastic fragments in the tuff are intermingled with considerable

material of water-lain, sedimentary origin. This material includes a variable abundance of quartz grains similar in shape to, though many somewhat larger than, those found in the slate that overlies the tuff and into which the tuff grades. Some detrital zircon has also been found in the tuff. It is also of interest to note that numerous small porphyroblastic garnets have been seen in thin sections of the tuff, even well towards the bottom. It is perhaps relevant to observe here that porphyroblastic garnets also occur in the overlying Onwatin slate. It would seem, therefore, that the pyroclastic material of the Onaping tuff, possibly including some fine ash, fell into and became intermingled with fine-grained water-lain muds or silts.

In conclusion, petrographic, chemical, and structural data suggest that the conspicuous breccia at the base of the Onaping formation is a tectonically brecciated, recrystallized quartzite that has been varyingly affected by soda metasomatism and later "micropegmatized"; and that, structurally, much of it has been deformed by drag-folding and disrupted by later tectonic transport. Furthermore, field data suggest that the overlying pyroclastics are layered deposits, the product of normal air-borne fall-out, and that they contain considerable water-borne sedimentary material.

I would like to thank Professor Hugh McKinstry and Mr. Frank Zurbrigg for helpful discussions, and the officers of the International Nickel Company for permission to publish the paper.

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Aqua Regia Extractable Lead and Molybdenum in Eruptive Rocks

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ABSTRACT

Various bodies of eruptive rock in southern British Columbia were sampled and analysed for lead and molybdenum, as well as for copper and zinc. The results indicate that each eruptive body tends to have a characteristic assemblage of trace elements, and that these trace element assemblages may be useful both in correlating rock masses and in determining which areas are most attractive for prospecting. In this type of work, chemical methods seem, at present, to be more applicable than either spectroscopic or X-ray fluorescence techniques.

IN recent papers (17, 18), the authors have commented on variations in the copper and zinc contents of some eruptive rocks. These variations apparently occur even within rock units which have been considered more or less homogeneous on the basis of available evidence. Some eruptive rock units have had exceptionally high copper, and some exceptionally high zinc contents; and in some places both copper and zinc contents have been abnormally high. In many instances, rocks anomalously high in one or both of these metals can be shown to be related to orebodies containing the anomalous metal or metals.

This brief note reports on the application of the same technique to the elements molybdenum and lead. One hundred and fifty-six samples from forty-five different occurrences of eruptive rocks mapped and described by the Geological Survey of Canada have been analysed. As may be noted, the results are sufficiently interesting to justify further work along these lines and, particularly, more detailed investigations of some of these batholiths about which a considerable amount of information is already available.

SAMPLING PROCEDURE

The sampling procedure has already been described in detail (18), and need only be mentioned. A three to five pound chip sample of as fresh material as it is practical to obtain is reduced to a representative sample of from 100 milligrams to 5 grams, depending on the amount of lead and molybdenum which is anticipated. Preliminary runs are normally made on two-gram samples.

ANALYTICAL PROCEDURE

The analytical procedure for lead has been described (19). It is based on an attack by *aqua regia*, and a dithizone mixed-colour determination. An aliquot of solution is tested for molybdenum by thiocyanate and iso-propyl ether extraction (20).

The samples have been finely ground, most of the feldspar being less than 200 mesh. Thus, it is possible that a substantial portion of their heavy-metal content has been extracted.

TABULATION OF RESULTS

The results of the various analyses are given in Tables I to VIII.

Shortly after the suites referred to in Table I had been collected, an anomalous igneous body was encountered. Nine samples from this body averaged 9 p.p.m. molybdenum and 66 p.p.m. lead. In spite of the fact

TABLE I

ROCKS GENERALLY REFERRED TO AS NELSON INTRUSIVES

Area	No. of samples	Rock type	Distance from recorded mineralization (miles)	Mo (p.p.m.)	Pb	Reference
Keremeos	5	Granodiorite	>2	<0.4	0.4	Bostock (3) Little (12)
Osoyoos	5	Granodiorite	>4	<0.4	<0.4	Bostock (3) Little (12)
Greenwood	5	Granodiorite	<¼	<0.4	<0.3	Little (10)
Beaverdell	5	Granodiorite	<¼	1	2	Little (10)
Beaverdell	5	Granodiorite	>5	<0.5	3	Little (10)
Beaverdell	1	Granodiorite	>10	0.4	2	Little (10)
Erie	5	Granite	>3	<0.5	6	Little (11)
Castlegar	10	Porphyritic granite	>14	<0.5	3	Little (11)
Monashee	5	Porphyritic granite	>12	<0.5	2	Little (10)

that no mineralization could be seen in hand-specimens, detailed exploration has been recommended for this area.

It might be felt that because the Sugar Loaf and Highland Valley samples (see Table VI) came from rocks associated with important copper mineralization, they might reasonably have been expected to carry more

TABLE II

ROCKS REFERRED TO AS VALHALLA INTRUSIVES

Area	No. of samples	Rock type	Distance from recorded mineralization (miles)	Mo (p.p.m.)	Pb	Reference
Beaverdell	1	Porphyritic granite	>5	0.4	2	Little (10, 12)
Carmi	1	Porphyritic granite	>5	<0.5	4	Little (10, 12)

molybdenum. However, the Guichon Creek batholith is actually a complex of batholithic rocks, and a sample of Bethlehem quartz diorite taken within half a mile of known mineralization ran 20 p.p.m. molybdenum and 6 p.p.m. lead. Obviously the rocks of the Guichon Creek batholith invite more detailed study.

Incidentally, a lead and zinc prospect is close to the sample taken at Siwash Creek.

TABLE III

ROCKS REFERRED TO AS CORYELL INTRUSIVES

Area	No. of samples	Rock type	Distance from recorded mineralization (miles)	Mo (p.p.m.)	Pb	Reference
Christina Lake	5	Quartz monzonite	>4	<0.4	4	Little (11)
Grand Forks	5	Quartz monzonite	>8	<0.5	7	Little (10)
Rossland	5	Quartz monzonite	<½	1	6	Little (11)
Ymir	5	Augite biotite monzonite	<1	1	31	Little (11)

Two suites which were collected at the same time as those of Table VII ran 127 p.p.m. molybdenum. Because they were also high in copper, the surrounding area, heretofore believed barren, is being investigated further.

TABLE IV

ROCKS YOUNGER THAN NELSON AND OLDER THAN CORYELL

Area	No. of samples	Rock type	Distance from recorded mineralization (miles)	Mo (p.p.m.)	Pb	Reference
Kruger Mt.	5	Syenite	>2	1.1	0.3	Bostock (3) Little (12)
Vernon	1	Granite	>4	1	4	Rice and Jones (16) Little (12)

TABLE V

ROCKS OF DEWAR CREEK BATHOLITH

No. of samples	Rock type	Mo (p.p.m.)	Pb	Reference
2	Biotite granodiorite	<0.3	1	Reesor (13)
1	Inclusion in above	<0.3	3	,,
1	Hornblende granodiorite	<0.6	2	,,
1	Inclusion in above	<0.4	1	,,
2	Porphyritic quartz monzonite	3	2.5	,,
1	Leuco quartz monzonite	<0.3	1	,,
1	Fine leuco quartz monzonite	<0.3	3	,,

TABLE VI
Intrusive Rocks of Southern Interior Plateau

Area	No. of samples	Rock type	Distance from recorded mineralization (miles)	Mo (p.p.m.)	Pb	References
Sugar Loaf, near Kamloops	2	Quartz diorite (Iron Mask batholith)	$<\frac{1}{4}$	2	2	Cockfield (7)
Rose Hill, near Kamloops	1	Quartz diorite	>2	<0.4	1	Cockfield (7)
Chase	1	Granodiorite	>10	<0.4	5	Rice and Jones (16) Jones (8)
Lac Le Jeune	2	Quartz diorite	>6	<0.4	2	Cockfield (7)
Siwash Creek	1	Quartz diorite (Otter Intrusive)	$<\frac{1}{4}$	1	44	Rice (14)
Highland Valley	19	Quartz monzonite to granodiorite (Guichon Creek batholith)	Various distances	<0.4	2	White, Thompson, and McTaggart (21)

TABLE VII
Rocks Generally Referred to as Coast Range Intrusives

Area	No. of samples	Rock type	Distance from recorded mineralization (miles)	Mo	Pb (p.p.m.)	References
North Arm	5	Granodiorite	>4	<0.5	2.0	Rice (15)
Burrard Inlet	3	Granodiorite	>8	<0.4	1.0	Armstrong (1)
North Vancouver	1	Granite	>6	<0.4	0.8	Armstrong (1)
Horseshoe Bay	1	Granodiorite	>10	<1.0	<1.0	Armstrong (1)
Sheltery Bay	2	Granodiorite	>10	<1.0	<1.0	Leroy (9)
Read Island	2	Granodiorite	>10	<1.0	<1.0	Bancroft (2)
Toba Inlet	2	Granodiorite	>3	<1.0	<1.0	Bancroft (2)
Texada Island	3	Granodiorite	$<\frac{1}{4}$	<1.0	<1.0	Leroy (9)

TABLE VIII

Area	No. of samples	Rock type	Distance from recorded mineralization (miles)	Mo	Pb (p.p.m.)	Reference
Malahat	5	Granodiorite	>10	<0.5	3	Clapp (6)
Saanich	5	Granodiorite	<2	<0.5	2	Rice (15)
Jordan River	5	Gabbro	>8	<0.5	0.5	Clapp (5)
Sooke	5	Gabbro (light)	>1	<0.5	0.5	Clapp (5)
Sooke	5	Gabbro (dark)	>1	<0.5	1	Clapp (5)

DISCUSSION OF RESULTS

In only four samples was there more than 1 p.p.m. of molybdenum extractable with *aqua regia*: two of these samples were from rock units known to be closely related to important copper mineralization, the Iron Mask batholith near Kamloops, and the Bethlehem quartz diorite in the Highland Valley area. Of the other two anomalous molybdenum rocks, one has resulted in an exploration programme, and the other, from the Dewar Creek area, remains without any obvious explanation. However, with so many of the samples carrying molybdenum below determinable limits for a two-gram sample, it is obviously unwise to speculate on these results. However, if in southern British Columbia an eruptive rock carries appreciably more than 1 p.p.m. of molybdenum extractable with *aqua regia,* then this rock would appear to merit further attention.

In terms of lead extractable with *aqua regia,* the rocks that have been analysed fall into three groups: those that run less than 1 p.p.m., those with from 1 to 10 p.p.m., and those with more than 10 p.p.m. Three suites were found to be in the last-named group: two, those from Ymir and Siwash Creek, are known to be near lead and zinc mineralization, and the third, mentioned at the bottom of Table I, is now the centre of an exploration programme.

Those rocks with from 1 to 10 p.p.m. of lead extractable with *aqua regia* may be related to heavy copper mineralization, as in the Highland Valley, or to appreciable amounts of potash feldspar, as is the case with the Coryell rocks and some of the granites and porphyritic granites of the Nelson intrusives.

The Beaverdell and Greenwood granodiorites were surprisingly low in lead when it is remembered that some of these samples came within a quarter of a mile of high-grade orebodies. This would suggest that the lead in these orebodies was not genetically related to those rocks, which merely provided a suitable host.

Some other observations may be made, which are much what one might anticipate, namely: rocks which are similar petrographically tend to have similar molybdenum and lead contents in any single metallogenetic province; within one metallogenetic province, there are variations in the amounts of lead and molybdenum, the lead probably reflecting its well-known relationship with potassium. The Coryell intrusives differ from the other intrusive rocks of southern British Columbia in tending consistently to have higher amounts of *aqua regia* extractable lead. Much more work must be done, and, in particular, detailed studies of well-exposed batholithic rocks must be made before it will be possible to assess the usefulness of these extractions with *aqua regia*. However, the simplicity of the technique, the fact that no expensive equipment is needed, and the practicability of integrating much of this work with routine geological investigations suggest that further work along these lines is justified.

Summary and Conclusions

It is possible to establish normal molybdenum and lead contents extractable with *aqua regia* of rocks. Anomalous amounts in rocks can be detected readily, and usually justify further investigations. Copper and zinc determinations can be made from the same sample, and a consideration of all four elements can be most rewarding.

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